MINISTRY OF EDUCATION

GHANA ASSOCIATION OF SCIENCE TEACHERS

Aviation and Aerospace Engineering

for Senior High Schools

Year 2

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FOREWORD

Ghana's new Senior High School Curriculum aims to ensure that all learners achieve their potential by equipping them with 21st Century skills, knowledge, character qualities and shared Ghanaian values. This will prepare learners to live a responsible adult life, progress to further studies and enter the world of work. This is the first time that Ghana has developed a Senior High School Curriculum which focuses on national values, attempting to educate a generation of Ghanaian youth who are proud of our country and can contribute effectively to its development.

The Ministry of Education is proud to have overseen the production of these Learner Materials which can be used in class and for self-study and revision. These materials have been developed through a partnership between the Ghana Education Service, teacher unions (Ghana National Association of Teachers-GNAT, National Association of Graduate Teacher -NAGRAT and the Coalition of Concerned Teachers - CCT) and National Subject Associations. These materials are informative and of high quality because they have been written by teachers for teachers with the expert backing of each subject association.

I believe that, if used appropriately, these materials will go a long way to transforming our Senior High Schools and developing Ghana so that we become a proud, prosperous and values-driven nation where our people are our greatest national asset.

Haruna Iddrisu MP

Minister for Education

SECTION

1 CLIMATOLOGY

Core Concepts in Aerospace

Aerodynamics and Propulsion

INTRODUCTION

Aeroplanes require an airstream flowing around them to fly. This airstream, however, is subject to the ambient weather conditions of the location where the aeroplane flies. Due to this, it is important for civil aviation bodies, airline operators and pilots to know the weather conditions of their flight route locations. The need for knowledge of weather has also been reinforced by some previous aircraft incidents and even fatal accidents whose causes were traced to poor weather conditions. This section covers the weather elements, the instruments used to measure them and how these weather elements affect air travel. It also discusses how atmospheric conditions change with altitude and how these changes affect the performance and operation of aeroplanes. At the end of this session, you should be able to identify and measure weather elements using appropriate instruments. Then, explain the impact of weather elements on flight and also, explain the impact of altitude on the state of the atmosphere.

Key ideas

- Adverse weather conditions can cause aircraft incidents and fatal accidents.
- Civil aviation organisations and airline operators rely on meteorological service agencies to provide them with accurate weather forecasts to aid in flight planning.
- The altitude at which an aircraft operates affects its performance.
- Weather forecast is a major contributor to flight planning in the aviation industry.

WEATHER AND ITS DEFINING ELEMENTS

The Earth's surface is surrounded by layers of gases. These layers of gases make up the atmosphere. From elementary earth science, we know that the Earth rotates about its axis while revolving around the Sun. We also know that the earth is spherical, and its axis of rotation is tilted. Due to factors like the spherical shape of the Earth and its axial tilt, the Earth's rotation and revolution and geographical features (like mountains, hills, valleys and waterbodies) on the Earth's surface, the Earth's surface experiences uneven heating by the Sun which results in different atmospheric conditions on different parts of the Earth's surface. As shown in **Figure 1.1** below, it can be seen that due to the spherical nature of the Earth, the areas around the equator receive the Sun's rays directly, while the areas close to the north and south poles receive the Sun's rays at a low angle of incidence. This makes the regions around the equator warmer than the regions around the poles.

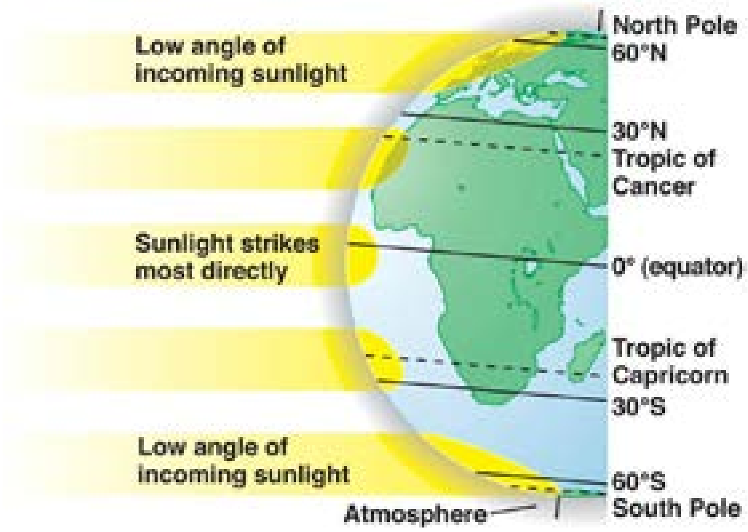

Figure 1.1: Uneven heating of the Earth (Factors affecting Climate)

These atmospheric conditions observed within a short period of time is called weather. The weather conditions in a particular geographical location can change within a day or even an hour. On the other hand, climate is the state of the atmosphere observed over a long period of time. A change in climate conditions in a particular geographical location can only be observed after the collection of the weather data of that location over long periods of time, usually spanning over two or three decades. Weather and climate deal with the same thing, with the only major difference being the time frame within which they are observed.

Elements of Weather

To describe the weather conditions in a geographical location, we often look out for certain features that characterise the weather conditions. For example, we could say it is often sunny in the Northern parts of Ghana while the forest areas receive rainfall frequently. Using the features of rainfall and sunlight, we are able to give a glimpse of the weather conditions in these areas in Ghana. These features, observable physical features that characterise the weather conditions in a particular area, are called weather elements. Besides rainfall and sunlight, the weather in a geographical location can be further described by elements like humidity, visibility, temperature, atmospheric pressure, cloud cover, wind speed and wind direction. Some of these major weather elements are explained below.

1. **Temperature:** This refers to how hot or cold the surrounding air is. It is due to the kinetic energy in the air molecules. Temperature is measured using an instrument called a thermometer. Thermometers may be digital or liquid-in-glass. Temperature is measured in degrees Celsius (°C), Kelvin (K) or Fahrenheit (°F).

Attach the thermometer to a structure or pole in a shaded, ventilated area. If using a liquid-in-glass thermometer, hang it securely to avoid breakage. Give the thermometer a few minutes to adjust to the outdoor air temperature before reading. Digital thermometers may adjust more quickly, while traditional thermometers may take a longer time (about 10 minutes).

Figure 1.2: A liquid-in-glass thermometer (How to Fix a Fridge That Isn't Cold Enough - HubPages)

Figure 1.3 Digital thermometer (Wind and Weather Outdoor thermometer)

2. **Precipitation:**
Precipitation forms a very important part in shaping the weather patterns of a geographical location. It refers to any form of water (whether liquid or solid) that falls from clouds to the Earth's surface. A large portion of the Earth's surface is covered with water. As the Sun's rays heat the Earth, the water evaporates, rises and cools to form clouds. When these clouds become too heavy to remain suspended in the air, they fall back down to the Earth. Precipitation may take different forms depending on the prevailing weather elements in a geographical

area. Precipitation may be in the form of rain, snow, sleet, hail, drizzle or freezing rain.

Figure 1.4: Forms of Precipitation (What Is Precipitation - Its Types, And Forms)

The most prevalent type of precipitation in Ghana is rain. Rainfall is measured using an instrument called a rain gauge. Rainfall is measured in millimetres (mm) of depth over a specific area.

To use a rain gauge, place it in an open area away from trees, buildings and other structures that could block or deflect rainfall. Make sure that the rain gauge is placed on a stable and level surface. After rainfall, check the water level in the rain gauge. Read the measurement scale at eye level and note the amount in millimetres. Take note of the time and date.

Figure 1.5: Rain Gauge (Rain Gauges For Home Use - How A Rain Gauge Can Be Used In The Garden | Gardening Know How)

3. **Atmospheric Pressure:**
   Atmospheric pressure, also known as air pressure, is the force exerted by the weight of the air above a given point on the Earth's surface. It influences wind, temperature and precipitation. Understanding atmospheric pressure is essential for

weather forecasting as it affects the movement of air masses and the development of weather systems. The instrument used for measuring atmospheric pressure is called a barometer. Atmospheric pressure is measured in millibars (mbar) or inches of mercury (inHg). At mean sea level, the atmospheric pressure is about 1013.25 mbar or 29.92 inHg.

Figure 1.6: A Barometer (Fischer Precision Aneroid Barometer)

4. **Humidity:** Due to the heating of water bodies on the Earth's surface, there is usually some amount of water vapour in the atmosphere. The amount of water vapour present in the atmosphere is known as humidity. Humidity is a key factor in weather as it affects both temperature and precipitation. Humidity is often expressed in two forms: absolute humidity, which is the total amount of water vapour in a given volume of air, and relative humidity, which is the percentage of water vapour in the air relative to the maximum amount the air can hold at a given temperature. A hygrometer is used to measure relative humidity.

Figure 1.7: A hygrometer *(*[Hygrometer insert movement 70mm diameter available in a choice of colour. - Time & Weather Instruments]*)*

5. **Wind:**
Wind is the movement of a large mass of air from one place to another. Due to the uneven heating of the Earth's surface, there are variations in atmospheric pressure at different points of the Earth's surface. Some regions have high atmospheric pressure, and other regions have low atmospheric pressure. In nature's attempt to balance this pressure gradient (that is, the difference in air pressure), air moves from the regions of high atmospheric pressure to regions of low atmospheric pressure. The higher the pressure gradient, the stronger the wind speed. Wind speed is measured in metres per second (m/s) or kilometres per hour (km/h). The instrument for measuring wind speed is an anemometer.

Figure 1.8: Anemometer *(*[File:Anemometer.jpg - Wikimedia Commons]*)*

As well as wind speed, it is often desirable to know the direction of prevailing winds. A wind vane is the instrument used to indicate the wind direction.

Figure 1.9: A wind vane *(*[File:Wind vane 05643.jpg - Wikimedia Commons]*)*

6. **Visibility:** Visibility in weather refers to the distance at which objects can be seen and recognised. It is important for driving and aviation safety, especially during take-off and landing. Poor visibility has been a cause of some fatal aviation accidents. The unit of measurement of visibility is feet or metres. It can be measured by sensors or by visual inspection. Consider the image below. Visibility

has been severely reduced due to fog. This condition can be dangerous to both the driver and the pedestrian.

Figure 1.10: Poor visibility

7. **Cloud cover:** When water evaporates from oceans and inland water bodies, it becomes gaseous and the water vapour rises upward. As it rises upwards, it cools down and condenses to form clouds. Cloud cover refers to the fraction of the sky covered by clouds at any given time. It is an important meteorological parameter that affects weather patterns, temperature, and sunlight reaching the Earth's surface. Cloud cover is typically expressed as a percentage, ranging from 0% (clear sky) to 100% (completely overcast).

Figure 1.11: Partial Cloud Cover

8. **Sunshine:**
This is the radiation from the Sun that we receive here on Earth in the form of light and heat. Sunshine is one of the major determinants of the weather conditions in a geographical location. The duration and intensity of sunlight that a particular region receives inform its temperature and general weather patterns. It is therefore important to be able to measure the intensity of sunlight and how long an area receives sunlight during the day. The instrument for measuring the amount of sunlight a geographical area receives is a sunshine recorder.

Figure 1.12: Sunshine recorder

Activity 1.1

Measuring Rainfall Using a Rain Gauge

1. Research on how a rain gauge is used to measure the amount of rainfall.
2. Visit a local weather station with your teacher to learn about the different elements of weather and how they are measured. Join a discussion after the visit to share your experiences with your classmates.
3. In a group of your classmates, measure the rainfall, wind speed and direction.
4. Using a laboratory thermometer, measure the ambient temperature on a particular day at the following times:

Table 1.1: Temperature recordings

Time	Temperature (°C)
8:00 am	
12:00 noon	
4:00 pm	

In pairs, use locally available materials to construct a simple wind vane. *Proposed materials:*

Pencil, straw, cardboard, glue, paper, pieces of wood, etc.

Safety Precautions

a. *Do not directly inhale the smell of glue being used.*
b. *Use the right tool for the right task.*
c. *Use appropriate personal protective equipment.*
d. *Be careful when using sharp tools.*
e. *Observe proper safety standards.*

Watch videos online on how to make a simple wind vane for a more visual guide.

Activity 1.2

Self-Assessment

Fill in the table below with weather elements and their respective measuring instruments.

Weather Element	**Instrument**
Rainfall	
	Thermometer
Wind speed	
Wind Direction	
Sunshine	
Humidity	
	Barometer

HOW WEATHER AFFECTS AIR TRAVEL

Weather plays a very important role in flight planning and performance. It has a direct impact on safety, efficiency and passenger comfort. Airline operators carefully consider weather reports during flight planning to ensure safe flight operations. Below are some weather factors and how they affect flight planning and performance:

1. **Wind:** Headwinds (winds blowing against the direction of flight) can slow the aircraft down, increasing fuel consumption and extending travel time. Tailwinds (winds blowing in the same direction as the aircraft) help reduce travel time and save fuel. Winds blowing perpendicular to the runway pose challenges during

take-off and landing, requiring skilful handling by pilots to avoid drifting off course. These types of winds are known as crosswinds.

Figure 1.13: An aeroplane landing in a crosswind (Pilot explains crosswinds landing | CNN)

Pilots and dispatchers consider prevailing wind conditions when selecting flight routes, opting for paths that minimise headwinds or take advantage of tailwinds. Wind conditions influence fuel burn rates. Headwinds can require more fuel, while tailwinds may reduce fuel needs.

2. **Visibility:** Good visibility is very important in air travel, especially during take-off, landing and low altitude flight. Reduced visibility affects the pilot's ability to see runways, obstacles, or other aircraft, making take-off and landing particularly challenging. Poor visibility may require the use of precision instrument landing systems (ILS). Pilots may need to divert to alternate airports if the destination has poor visibility, especially if it lacks advanced instrument landing systems. This may cause scheduled flights to be delayed. Poor visibility could be due to fog, rain or snow. This necessitates the use of Instrument flight rules, where pilots rely on aircraft instruments to navigate. Visual flight rules, which allow pilots to navigate by sight, are only possible when visibility is good.

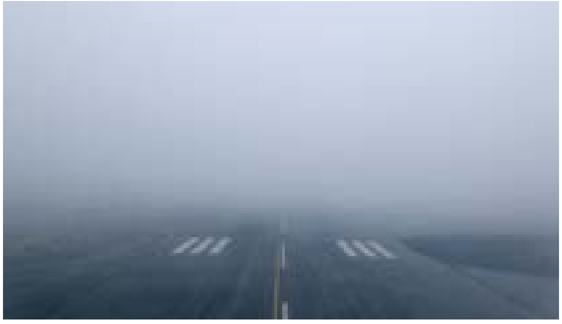

Figure 1.14: A foggy runway (Foggy morning causes flight delays, cancellations at Auckland Airport | Newshub)

3. **Precipitation:** Precipitation in the form of heavy rain can reduce visibility and affect runway conditions, leading to hydroplaning during take-off and landing. In very cold regions, snow accumulation on runways or aircraft surfaces can severely impact performance. Ice built up on wings and control surfaces reduces lift and increases drag, potentially causing dangerous stalls. Anti-icing and de-icing procedures may be necessary in such conditions.

Figure 1.15: Ice formation on aircraft wing (NTSB Calls For FAA, GAMA To Work On New Aircraft Icing Alert System – Disciples of Flight)

In the case where the precipitation is in the form of hail, severe damage could be caused to aircraft structures and installations, leading to diversions, delays or even flight cancellations.

4. **Turbulence:** Turbulence occurs when irregular air currents disrupt the smooth flow of air, causing the aircraft to experience sudden, unpredictable movements. It affects flight by causing discomfort to passengers and can make control of the aircraft more challenging for pilots.

5. **Thunderstorms:** Thunderstorms can produce severe turbulence, strong winds and wind shear, which are dangerous to aircraft and cause discomfort to passengers. Lightning strikes associated with thunderstorms though rarely catastrophic, can cause damage to aircraft electrical systems or minor structural issues. Thunderstorms are typically avoided. Pilots use weather radar to detect and avoid storms or request for alternative routes.

6. **Temperature:**
   An increase in air temperature reduces the density, which leads to a decrease in the lift force that a wing generates as will be shown in the next session. Decreased air density also affects engine performance. On the other hand, colder air improves engine efficiency and the higher density associated with colder air improves lift generation. However, extremely low temperatures can cause ice formation on the leading edge of wings and tail, engine nacelles and nose of the aircraft which disrupts the airflow around the aircraft leading to reduced aerodynamic efficiency. Low temperatures also have adverse effects on fuel and hydraulic systems.

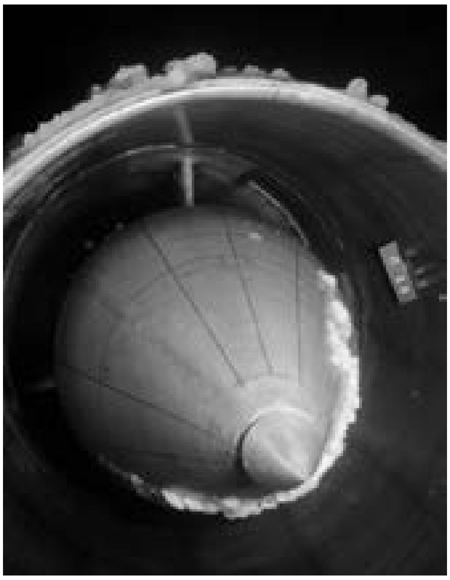

Figure. 1.16: Ice formation on engine inlet

7. **Cloud cover:**
Dense cloud cover can obscure the terrain, requiring instrument flight rules and increasing reliance on instruments for navigation and landing. Flying through thick clouds increases the chances of experiencing turbulence and icing. Flight routes may be adjusted to avoid heavy cloud formations that could result in turbulence or icing.

Figure 1.17: Aircraft flying through heavy cloud cover

Weather significantly impacts flight planning and performance, influencing route selection, fuel consumption, safety protocols, and even passenger comfort. Proper pre-flight weather analysis and continuous monitoring during flight are crucial for safe and efficient operations. By anticipating and responding to adverse weather conditions, pilots can make informed decisions that mitigate risks and enhance the overall safety of air travel.

The Ghana Meteorological Agency provides the Ghana Civil Aviation Organisation and airline companies with weather forecast data to aid in their flight planning and operations. If adverse weather conditions are expected, an alternative flight route may be used, or the aircraft may need to land at the nearest airport until weather conditions become convenient for flight.

Activity 1.3

Impact of Weather Elements on Flight

1. Watch video documentaries on the Tenerife air crash incident that occurred on 27 March 1977 and document your findings. (https://www.youtube.com/watch?v=wpQE17liK7A)
2. Join a group of your classmates to discuss the elements of weather that you have experienced within your communities.
3. In your group brainstorm the impact of weather elements on flight.
4. In your group also discuss the role of the Ghana Meteorological Agency in fostering safety in air travel.
5. Research the air crash incident of Allied Air Boeing 727-221F cargo aircraft at Accra on 2nd June 2012. (https://www.baaa-acro.com/crash/crash-boeing-727-221f-accra-10-killed) Write a short essay on how adverse weather conditions may have contributed to the incident.

Activity 1.4

Self-Assessment

What precaution(s) must a pilot take when flying in icy weather conditions?

Structure of the Atmosphere

The Earth's atmosphere is in layers, with each layer having different features from the others. Let us now consider each layer and look at their features.

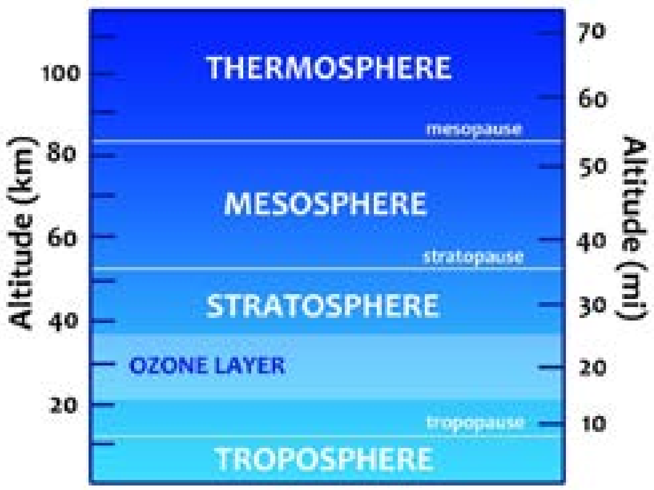

Figure 1.18: Layers of the Atmosphere

1. **Troposphere:** This is the layer of air closest to the surface of the Earth. It is where all life and weather phenomena like clouds, precipitation and wind occur. It is relatively dense compared with the other layers of the atmosphere and contains about 75% of the atmosphere's mass and most of the water vapour. It is made up of gases like Nitrogen, Oxygen, Argon, Carbon Dioxide and water vapour.

   The Troposphere begins from the Earth's surface up to about 8 - 15 km, depending on the latitude. The thickness of the troposphere is not uniform over the entire Earth's surface. It is generally thicker at the equator due to warmer air rising more forcefully and thinner at the poles, where the air is cooler. Most flight operations occur in the troposphere. Pressure decreases with altitude in the troposphere. At sea level, the air pressure is around 1013.25 hectopascals (hPa). However, the pressure can be as low as 200hPa at the top of the atmosphere.

   Air density also decreases with altitude in the troposphere. This means the air is "thinner" at high altitudes. At higher altitudes, due to the lower air density, the aircraft needs to achieve a higher ground speed to generate enough lift. This requires a longer runway for take-off. In simple terms, the aircraft must accelerate to a higher speed before it can leave the ground, and this takes more time and distance.

   Engine performance is also affected by altitude. Aircraft engines require an air intake to generate thrust. At higher altitudes, they take in less air due to the low air density at high altitudes. This results in reduced engine thrust. This may result in reduced payload capacities for aircraft taking off from high altitudes. The tropopause marks the boundary between the troposphere and the stratosphere (which is the layer above the troposphere).

2. **Stratosphere:** Above the troposphere is the stratosphere. It begins from the tropopause to an altitude of about 50 km. Unlike the turbulent and weather-prevalent nature of the troposphere, the stratosphere is more stable and plays a crucial role in protecting the Earth.

   One of the defining features of the stratosphere is that temperature increases with an increase in altitude, contrary to that of the troposphere, where temperature decreases with an increase in altitude. This increase of temperature with altitude is basically due to the presence of the ozone layer in the stratosphere, which absorbs ultraviolet (UV) radiation from the Sun and converts it into heat, warming the stratosphere.

   The ozone layer is located within the stratosphere, generally between 20 and 30 km above the Earth's surface. It is one of the most crucial features of the stratosphere and plays a vital role in absorbing and filtering out harmful ultraviolet (UV) radiation from the Sun.

   Without the ozone layer, more UV radiation would reach the Earth's surface, leading to severe health and environmental consequences. The topmost part of the stratosphere is called the stratopause.

3. **Mesosphere:**

This is the third layer of the atmosphere. It sits directly above the stratosphere and extends from approximately 50km to about 85km above the Earth's surface.

Temperature in the mesosphere decreases with increasing altitude. This layer has the coldest temperatures. The uppermost part of the mesosphere has temperatures reaching below -90°C.

The air density in the mesosphere is extremely low. Air pressure is very low in the mesosphere. The air density decreases as you go higher through the mesosphere.

One of the most fascinating phenomena of the mesosphere is that it is here where meteors burn up as they enter the Earth's atmosphere.

a. When a meteor (often called a shooting star) enters the Earth's atmosphere at high speeds, it encounters increasing friction with air molecules in the mesosphere.
b. This friction causes the meteor to heat up and disintegrate before reaching the surface.
c. The mesosphere thereby acts as a protective shield, preventing most meteors from reaching the Earth's surface and causing damage.

Figure 1.19: A burning meteor (NASA releases photo of a meteor blazing across Nevada skies)

4. **Thermosphere:** The thermosphere is the fourth layer of the atmosphere, located above the mesopause. It extends from approximately 85km to around 600km above the Earth's surface. The thermosphere is named after the Greek word "thermo", which means heat. Temperatures in this layer can soar up to extremely high levels. Temperature increases with altitude in this layer. At its lower boundary, the temperature is still low; however, as you ascend, the temperatures reach up to over 500 to 2000 °C. Air pressure in the thermosphere is extremely low—just a tiny fraction of what it is at sea level. This means that although temperatures are high, the thermosphere does not have enough density to generate pressure or significant resistance for objects moving through it. The International Space Station can be found in the thermosphere.

Figure 1.20: The International Space Station -- ISS

5. **Exosphere:** The exosphere is the outermost layer of Earth's atmosphere, where the atmosphere gradually fades into the vacuum of space. It begins roughly at an altitude of 600 km and can extend up to 10,000 km above Earth's surface, though the exact boundary is not well-defined. In this region, the atmosphere is extremely tenuous, with very few gas particles, and there is little to no interaction between them. While the exosphere is considered part of Earth's atmosphere, it is so sparse that it behaves more like outer space.

INTERNATIONAL STANDARD ATMOSPHERE

The International Standard Atmosphere (ISA) is a model established to provide a standardised framework for the Earth's atmosphere at various altitudes. Developed by the International Civil Aviation Organisation (ICAO), the International Organisation for Standardisation (ISO), and other scientific bodies, the ISA serves as a baseline reference for aircraft performance calculations, aerodynamic analysis, and aviation-related engineering. It is crucial in aviation and aeronautics for ensuring consistency and accuracy when comparing aircraft performance under different conditions.

The ISA model assumes a specific set of average atmospheric conditions that vary with altitude, including temperature, pressure, and density. These values represent an idealised "standard" atmosphere, which pilots and engineers use as a reference rather than a representation of actual, real-time atmospheric conditions.

1. **Standard Sea-Level Conditions**
   The ISA defines a set of conditions at sea level, which is the reference level for calculations. These conditions are:

   Temperature: 15 ^{0}C

   Pressure: 1013.25 hPa

   Density: 1.225 kg/m^3

These values serve as a benchmark for calculating deviations in real atmospheric conditions, allowing pilots and engineers to make necessary adjustments to optimise aircraft performance.

2. Temperature profile

The ISA models the atmosphere to have a reduction in temperature as altitude increases up to an altitude of 11000m above sea level. There is a 6.5 ^{0}C reduction per kilometre. This value is commonly called the lapse rate.

Above 11000 m, the temperature remains constant at -56.5 ^{0}C up to an altitude of 25,000 m. The figure below shows the variation of temperature with altitude in the International Standard Atmosphere. Altitude in kilometres is indicated on the vertical axis and temperature in Kelvin on the horizontal axis.

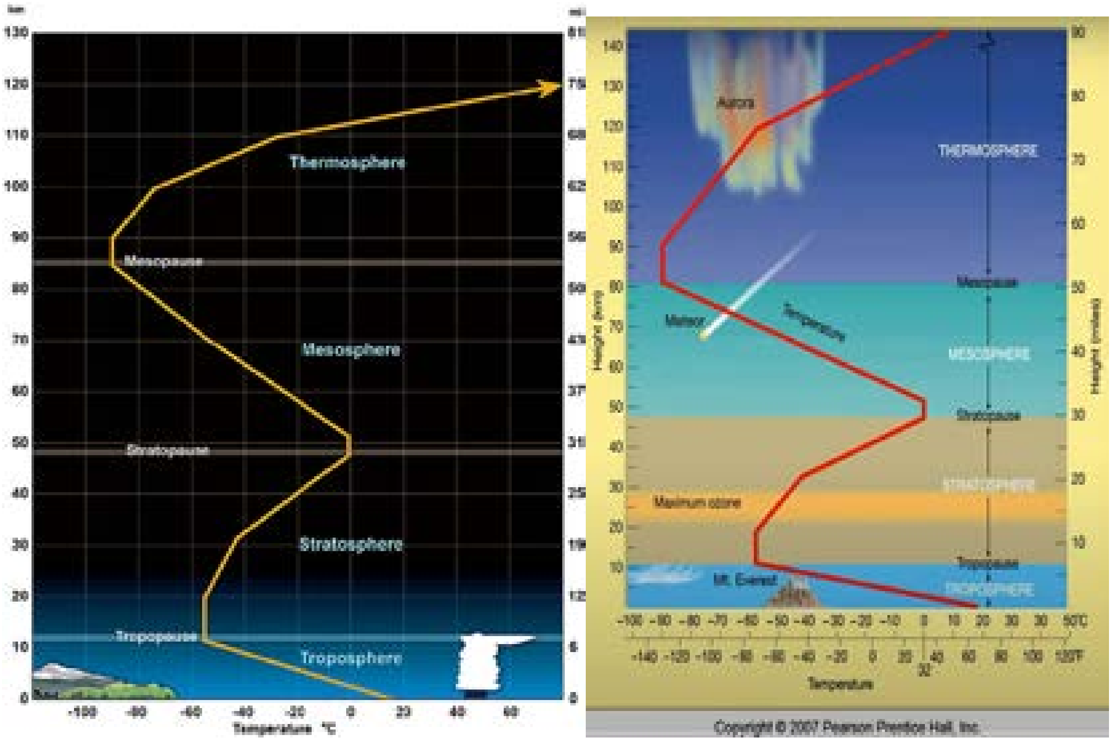

Figure 1.21: Temperature profile of the ISA

https://www.researchgate.net/figure/Average-temperature-profile-for-the-layers-of-the-Earths-atmosphere-Image-credit-NOAA_fig2_350342329

3. Pressure Variation with Altitude

Pressure also decreases with altitude in the ISA. Since atmospheric pressure is highest at sea level and decreases with height, aircraft performance (especially engine power and lift) is directly influenced by these variations. The ISA provides a mathematical model for calculating pressure at any altitude, which is used to:

a. Adjust altimeter settings to reflect true altitude.

b. Calculate true airspeed (TAS) and density altitude.

A lower pressure at higher altitudes results in reduced air density, which in turn affects aircraft performance. For example, reduced pressure and density means an aircraft may need a longer runway for take-off or will have a lower rate of climb.

The ISA provides a consistent standard that can be used across the aviation and aerospace industries. Engineers use the ISA to design and test aircraft in a simulated environment that represents average atmospheric conditions. This ensures that aircraft performance data such as climb rate, fuel consumption and range can be accurately calculated based on the ISA and the altitude in question. Pilots also rely on the ISA to calculate take-off performance, climb rates, fuel burn and required runway lengths. Knowing standard atmosphere values helps pilots understand deviations caused by real-time conditions.

Altimeters in aircraft are calibrated according to ISA pressure values. This allows for accurate altitude readings, which are essential for safe separation between aircraft and accurate navigation.

The International Standard Atmosphere has some limitations. It assumes average conditions that usually do not match actual atmospheric conditions. Factors like humidity, wind, turbulence and real-time temperature variations are not accounted for, so pilots and engineers must adjust for these deviations.

The ideal gas equation, $P = \rho RT$ can be used to solve for the pressure (P) or density (ρ) in the atmosphere at any altitude knowing the temperature and either the density or pressure, respectively. The value of R for air is 287 J/kg/K.

A table of atmospheric properties in the ISA is provided in Appendix A. Often, it is desired to find a value that is not explicitly listed in the table. In this case, it is necessary to interpolate between the two closest values. The following equation may be used:

where the unknown point lies between the two known points (x_1, y_1) and (x_2, y_2).

Activity 1.5

Layers of the Earth's Atmosphere

1. Join a small group of your classmates and discuss your understanding of the layers of the Earth's atmosphere.
2. Research the fundamental principles and equations that were used to model the ISA. Write down your findings below.
3. In your group brainstorm your understanding of the effect of International Standard Atmosphere on flight planning and create a group presentation to be delivered to the whole class.

Activity 1.6

Self-Assessment

Make a sketch on cardboard of the layers of the atmosphere and label the respective layers. Indicate on the sketch how temperature varies with altitude according to the International Standard Atmosphere. You may refer to **Figures 1.18** and **1.21** for guidance.

EXTENDED READING

1. Ghana | Bureau of Aircraft Accidents Archives (baaa-acro.com)
2. Aviation Weather Center
3. SkyVector: Flight Planning / Aeronautical Charts

Review Questions

1.

   a. Which type of precipitation is most common to Ghana's region?
   b. List the instruments used to measure the following weather elements:
      i. Sunshine
      ii. Temperature
      iii. Rainfall
      iv. Relative humidity
      v. Wind speed
      vi. Wind direction
   c. List the layers of the atmosphere in order of increasing altitude.

2.

   a. Based on your knowledge of weather elements, which major season in Ghana is characterised by very low levels of humidity.
   b. What are two factors that make it difficult for aeroplanes to operate at very high altitudes?

3.

   a. Using the lapse rate of the International Standard Atmosphere in the troposphere, if the temperature at sea level is 15 ^{0}C, what will be the temperature be at an altitude of 8,850 m above sea level?
   b. Knowing that the density at this altitude is 0.429 kg/m^3, determine the air pressure.

4. Consider a cargo aircraft getting ready to transport a heavy payload from an airstrip at an altitude of 50m above sea level. The destination is an airfield at an altitude of 3500m above mean sea level. Drawing from your knowledge of the atmosphere, highlight some factors that could impact the flight. Suggest measures that could be put in place to help execute the operation.

SECTION

2

FORCES ON AN AIRCRAFT

Core Concepts in Aerospace

Aerodynamics and Propulsion

INTRODUCTION

For an aircraft to take off and stay in the air, several forces act on it. These forces include lift, weight, thrust, and drag, all of which interact to determine how an aircraft takes off, flies, and lands. Aircraft designers and engineers consider these forces when designing planes to ensure optimal performance, depending on the aircraft's purpose.

In this section, we will explore how these forces affect an aircraft's flight. We will examine the principles of aerodynamics that enable aircrafts to take off, stay in the air, and land safely.

By the end of this section, you will understand how aerodynamics influences the different designs of aircraft and how these principles apply in the real world.

Key ideas

- Aircraft wings are designed to achieve the desired aerodynamic properties and stability for the aircraft's purpose with little drag associated.
- Drag is a force that opposes an aircraft's motion in flight
- Lift and drag are affected by multiple factors and can be calculated using their equations.
- Lift is generated by pressure differences around an aerofoil.
- Proper weight distribution in the aircraft helps achieve stability

INTRODUCTION TO AERODYNAMICS

When a solid object moves through air, the air exerts stresses on the object. These stresses are in the form of pressure and shear stress. Understanding how moving air interacts with objects is crucial for many industries. Having proper knowledge of aerodynamics is necessary for the design of aircraft, cars, wind turbines, propellers, air-breathing engines and tall structures like bill boards and skyscrapers. Consider an engineer designing a high-rise building. It would be of interest to know the range of magnitudes of the prevailing winds and direction so as to ensure the building is designed to be capable of withstanding the strongest possible wind.

Figure 2.1: Wind Turbines (38 High Def Wind Turbine Pictures From Around the World)

Figure 2.2: F-22 Jet Fighter (Archivo: F-22 Raptor edit1 (cropped).jpg - Wikipedia, la enciclopedia libre

As we move through this section, we will come across more practical applications of aerodynamics. Aerodynamics can be defined as the study of moving air and how it interacts with solid bodies. This branch of physics helps us understand how objects move through the air by applying fundamental physics principles. Anything that comes into contact with moving air, such as an aircraft, car or a kite, is subject to the laws of aerodynamics.

BASIC AERODYNAMIC VARIABLES

Before we dive deeper into aerodynamics, let's review some common terms and variables you'll encounter. Understanding these terms will help you connect the concept of aerodynamics to everyday life. Some of these terms might already be familiar from your physics classes, and we'll explore how they relate specifically to aerodynamics.

Mass: The mass of an object refers to the amount of matter it contains, and its SI unit is the kilogram (kg). Unlike weight, which varies, mass remains constant regardless of location. In aerodynamics, mass is crucial because it influences an object's resistance to changes in speed and balance during flight.

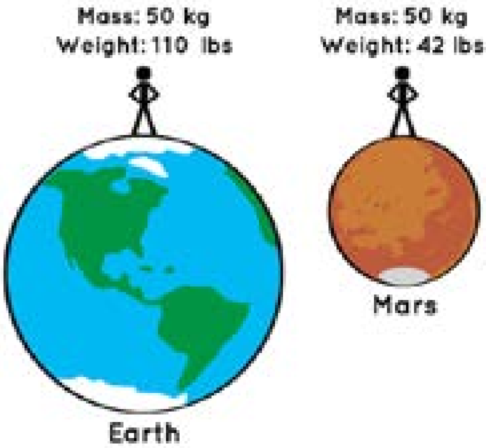

Figure 2.3: Mass and weight on different planets with different effects of gravity (Mass & Weight)

Mass measures the amount of substance an object contains; weight, however, is an indication of the gravitational pull acting on the body. Weight and mass are related by the mathematical expression,

Where;

W is the weight of the body in Newton (N)

m is the mass in kilograms (kg)

g is the acceleration due to gravity in metres per second squared (m/s^2)

As shown above, weight is a product of mass and acceleration due to gravity. A body may have a weight of 50N on the surface of the Earth. However, the same body will have zero weight in outer space even though the mass remains the same. This is because the gravitational pull of the Earth in outer space is practically zero. On another planet where the gravitational pull is different from that on Earth, the body will have a different weight.

Volume: Every form of matter takes up space, and the space it occupies is called volume. In other words, volume measures how much space matter occupies. It gives an indication of the size of the object. The SI unit for volume is the cubic metre (m^3).

Density: Density is influenced by both mass and volume. In physics, it is defined as the mass per unit volume of an object, meaning it measures how much mass is packed into a given space. The SI unit for density is the kilogram per cubic metre (kg/m^3). In aviation, the density of the air around an aircraft plays a key role in determining the aerodynamic forces acting on it and can influence how high the aircraft can fly. Note that the density of an object is not about size, it is usually a property of the material.

Consider a typical soccer ball and coin. The ball has more mass and volume than the coin. However, the coin is denser than the ball. This is firstly due to the material the coins are made of. Secondly, the ball is filled with air, which is low in density making the overall density of the ball low. It is for this reason that a ball will float atop water but a small coin will sink to the bottom.

Velocity: Velocity describes how fast an object moves and in what direction. It is defined as the rate of change of an object's position over time, considering both the speed (magnitude) and the direction of the movement relative to a reference point. The SI unit of velocity is metres per second (m/s).

Velocity is mathematically expressed as,

Where;

Δr is the displacement (along a straight line) and Δt is the time interval

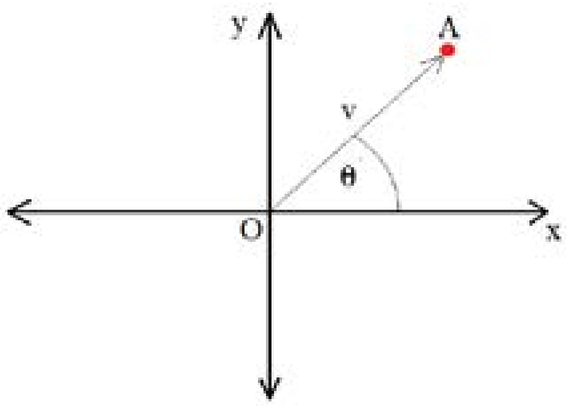

Figure 2.4: Velocity vector (Source: NACCA, 2024)

Consider the image above. A particle, shown by the red dot, moves from point O to point A along a straight path as indicated by the blue line OA. Assuming the displacement between O and A is eight metres and the particle took 1.6 seconds to cover that interval. The velocity can be calculated as follows:

Pressure: When a force is applied to the surface of an object, it creates pressure. Pressure is the amount of force acting on a specific area of that surface. It is calculated by dividing the force by the area over which it is applied. The SI unit of pressure is the Pascal (Pa), which is equal to one Newton per square metre (N/m^2). This means that 1 Pascal is the pressure exerted when a force of 1 Newton is applied over an area of 1 square metre. Pressure is mathematically expressed as

Where;

P is the pressure being exerted in N/m^2

F is the force in N

A is the area over which the force is applied expressed in m^2

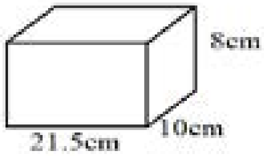

Figure 2.5: Building block

Let's take a classic example. Consider a building block of mass 15kg with dimensions as shown in **Figure 2.5.** If it lies on one of its faces with dimensions of 21.5cm and 10cm as shown above, let's calculate the pressure it exerts on the floor.

First, we need to know the force the block applies on the floor. Assuming acceleration due to gravity is 9.81m/s^2 on earth, the weight will be,

Now we need to calculate the area of the face it sits on and since it sits on a rectangular face, we can find the area.

$$A = 0.215 \times 0.1$$

$$A = 0.0215\ m^2$$

Therefore, the pressure it exerts on the floor is

$$P = \frac{147.15}{0.0215}$$

$$P = 6844.19\ \frac{N}{m^3}$$

Flow: An interesting concept in aerodynamics is flow. Flow refers to the movement of fluids – air in our case – through a given point over time. It happens because of unbalanced forces acting on the fluid and continues until those forces are balanced. A simple example of flow is water falling from a great height, like a waterfall.

Fluid flow can be categorised based on its characteristics. Below are some common types of flow:

1. ***Compressible and Incompressible Flow:*** A compressible fluid is one whose volume changes during flow. In contrast, an incompressible fluid does not change in volume; its volume remains constant. In terms of density, a compressible fluid's density changes at different points during flow, while the density of an incompressible fluid stays the same throughout. Air is very compressible. Water on the other hand, is practically an incompressible fluid.

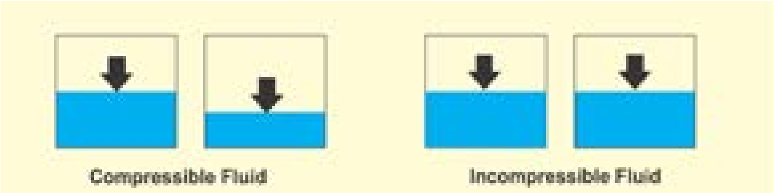

Figure 2.6: Compressible and Incompressible Fluid Flow (Compressible and Incompressible Fluid Flow)

2. ***Laminar and Turbulent Flow:*** In laminar flow, the fluid moves smoothly in parallel layers with no disruptions. On the other hand, turbulent flow is irregular and involves multiple instabilities.

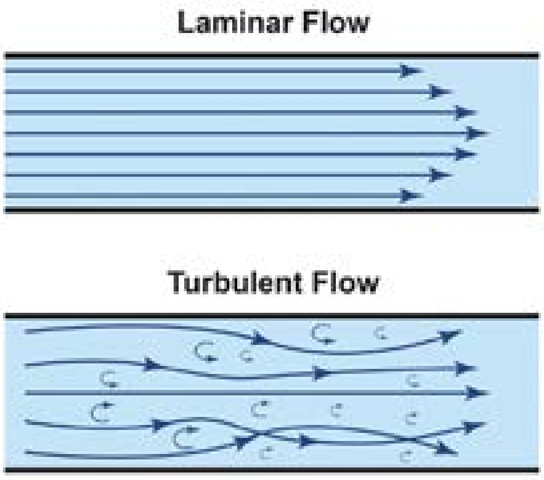

Figure 2.7: Laminar and Turbulent Flow (Laminar versus turbulent flow)

Mach Number (M): The Mach number is a way to describe how fast an object is moving compared with the speed of sound in the surrounding medium. For example, when an aircraft flies through the atmosphere, its Mach number is the ratio of the aircraft's speed to the speed of sound in the air. Mathematically, this can be written as:

Where;

v is the speed of the aircraft and

a is the speed of sound, considered to be 340 m/s at sea level.

Based on the Mach number, flow into different categories:

Subsonic	M < 1	Speed of flow is below the speed of sound
Sonic	M = 1	Speed of flow is equal to the speed of sound
Transonic	Mach 0.8 to Mach 1.2	Speed of flow is around the speed of sound
Supersonic	Mach 1 to Mach 5	Speed of flow is faster than the speed of sound

Hypersonic	M > 5	Speed of flow is extremely high, well beyond the speed of sound

Boundary Layer and Flow Separation: The boundary layer is a thin layer of fluid that forms along the surface of an object, such as an aircraft wing, as it moves through the air. This layer starts thin at the leading edge and thickens as it moves towards the trailing edge. Typically, the flow within the boundary layer is laminar near the leading edge and becomes turbulent closer to the trailing edge. As the fluid flows along the surface, the boundary layer can separate from the surface when the surface curves or changes direction. This process is known as flow separation and can negatively impact the performance of the aircraft by reducing lift and increasing drag.

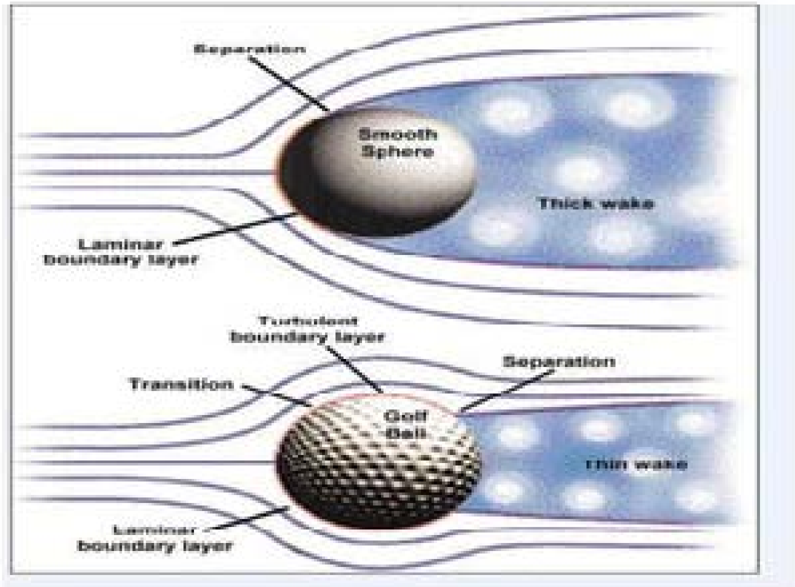

Figure 2.8: Demonstrating Boundary Layer and Flow Separation (External Flows)

Conservation of Matter and Mass Flow Rate

The Law of Conservation of Matter is a key principle in classical physics. It states that matter cannot be created or destroyed in an isolated system. This means the amount of matter in a closed system remains constant; no new matter is added, and none is lost. To better understand this, imagine water flowing through a tube. If we look at a specific section of the tube (as shown in **Figure 2.9**), the amount of water entering at point A must equal the amount of water exiting at point B, assuming there are no leaks or other changes. If more water enters at A than leaves at B, it would mean matter is being destroyed somewhere in the tube, and if more water leaves at B than enters at A, it would mean matter is being created somewhere in the tube. Both situations would violate the Law of Conservation of Matter.

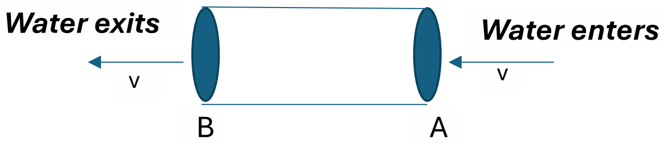

Figure 2.9: Section of tube with flowing water

In the diagram above, the water enters and exits the tube at the same velocity (v) because the cross-section of the tube remains uniform. Now, let's consider a scenario where the inlet diameter (D), with a cross-sectional area of A_1, is larger than the outlet diameter (d), with a cross-sectional area of A_2. The conical shape of the tube is shown in **Figure 2.10**. In this case, water enters the tube at the inlet with a velocity of v_1 and exits at the outlet with a different velocity, v_2.

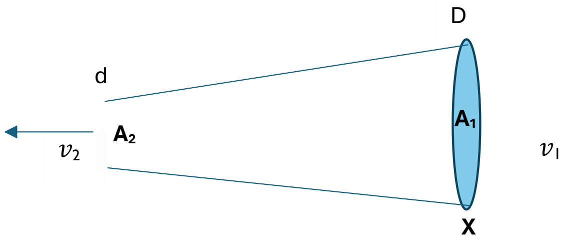

Figure 2.10: Section of a conical tube

By the law of conservation of matter, the amount of water entering a conical tube should be the same as the amount exiting at any given time. This leads us to the concept of **mass flow rate**, which is the amount of a substance (usually a fluid) that flows across a boundary in a certain amount of time. Mass flow rate is measured in kilograms per second (kg/s). The formula for mass flow rate is:

$$\text{Mass flow rate } (M) = \text{density } (\rho) \times \text{cross-sectional area } (A) \times \text{velocity } (\upsilon)$$

This can be written as:

$$M = \rho A \upsilon$$

Since the mass of water entering must equal the mass of water exiting at any point in time, the mass flow rate at the inlet must equal the mass flow rate at the outlet. Hence, we can write,

$$\rho A_1 \mathrm{v}_1 = \rho A_2 \upsilon_2$$

The above equation is called the continuity equation. Assuming the flow is incompressible (meaning its density doesn't change), the equation becomes:

$$A_1 v_1 = A_2 v_2$$

This is because the density (ρ) is the same at both the inlet and outlet, and thus it cancels out.

Since $A_1 v_1 = A_2 v_2$, and A_2 is smaller than A_1, this means v_2 (velocity at the outlet) must be larger than v_1 (velocity at the inlet) to keep the equation balanced. Therefore, the water flows faster at the outlet. This equation is known as the **continuity equation for incompressible flow** and is based on the principle of conservation of matter.

Forces of Flight

In Year 1, you learned about the four major forces that act on an aircraft in flight: lift, weight, drag, and thrust. We will take a closer look at these forces, how they are generated and how they influence flight.

For an aircraft to fly, it needs to generate an upward force that equals or exceeds its **weight**. This upward force is called **lift**. On a fixed-wing aircraft, the lift is generated by the wings while on a rotary wing aircraft, it is generated by the spinning rotor blades. As the aircraft moves through the air, it also encounters air resistance, which we call **drag**. And finally, for the aircraft to move forward, its engine must generate a force to propel it forward. This forward force is called **thrust**.

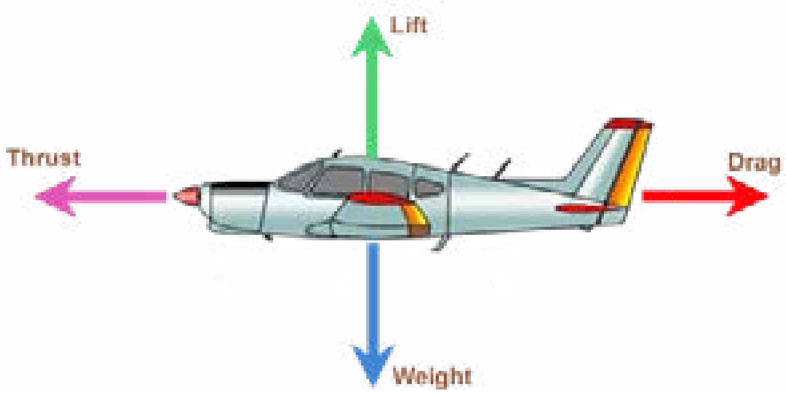

Figure 2.11: Forces of acting on an aircraft (Aerodynamics of Flight)

Activity 2.1

Discussion and Presentations

1. Divide into small groups, and each group will choose one of the concepts discussed above (mass, volume, density, pressure, velocity, boundary layer, flow separation, Mach number, etc.). You may also select an aerospace concept that was not discussed in the text above.
2. In your groups, discuss and create simple definitions of your chosen concept. Use real-life examples to help explain the concept. For instance, you might think about how mass or pressure affects a car, an aeroplane, or even a balloon.
3. Illustrate your chosen concept on a cardboard poster or PowerPoint presentation. Your poster should include:

a. The definition of the concept in simple terms.
b. At least one real-life example of the concept.
c. A diagram or visual aid to help explain the concept.

Be creative! Make sure your presentation is clear and engaging for others to understand.

4. Pair up with a classmate then run a 100-metre race while being timed with a stopwatch to determine the time it takes each of you to complete the 100-metre sprint. Then calculate your own average velocities based on the time it took to complete the sprint.
5. Research the effect of boundary layers on the skin of a flying aircraft. Create a PowerPoint presentation using the following slide headings:

Slide 1: Title Slide

- *Title: The Effect of Boundary Layers on the Skin of a Flying Aircraft*

Slide 2: Introduction

- *Overview of Boundary Layers*
- *Importance in Aerodynamics*

Slide 3: The Boundary Layer Concept

- *What is a Boundary Layer?*
- *Types of Boundary Layers*

Slide 4: Boundary Layer Development on Aircraft Skin

- *From Leading Edge to Trailing Edge*
- *Flow Separation*

Slide 5: Effects on Drag and Lift

- *Skin Friction Drag*
- *Form Drag and Pressure Drag*
- *Lift Production*

Slide 6: Factors Influencing Boundary Layer Behaviour

- *Speed and Mach Number*
- *Surface Roughness*
- *Aerofoil Shape*

Slide 7: Boundary Layer Control Techniques

- *Boundary Layer Suction*
- *Vortex Generators*
- *Surface Modification*

Slide 8: Boundary Layers at High Speeds

- *Transonic and Supersonic Flow*
- *Shock Boundary Layer Interaction (SBLI)*

Slide 9: Aircraft Surface Design and Materials

- *Impact on Aircraft Skin*
- *Long-Term Effects*

Slide 10: Case Study: Boeing 787 or Concorde

- *Boeing 787: Use of smooth composite materials to reduce drag and manage boundary layers efficiently.*
- *Concorde: How high-speed flight challenges boundary layer control and the impact of supersonic speeds on aircraft skin.*

Slide 11: Summary and Conclusions

- *Key Takeaways*
- *Future Outlook*

Activity 2.2

Self-Assessment

1. Using the Law of Conservation of Matter, explain how water flow in a tube can relate to fluid flow around an aircraft.
2. Describe the continuity equation for incompressible flow. Why is this equation important for understanding how fluids move around an aircraft?
3. Based on your knowledge of the four aerodynamic forces (lift, weight, drag, and thrust), consider the following:
   - **a.** What must an aircraft do to maintain level flight?
   - **b.** What happens if the lift force is less than the aircraft's weight?

The Aerofoil

Aerofoils are commonly found in items of machinery that are generally associated with moving air. They are found on aircraft wings and tails, helicopter rotor blades, gas turbine engine blades, wind turbine blades, propellers, racing cars and more. An aerofoil is a shape specifically designed to enhance certain aerodynamic properties. In wings, they are optimised to generate lift while creating as little drag as possible. There are various types of aerofoil designs, as shown in **Figure 2.12**. The aerofoil generates lift by taking advantage of the pressure difference between its upper and lower surfaces as air moves over it.

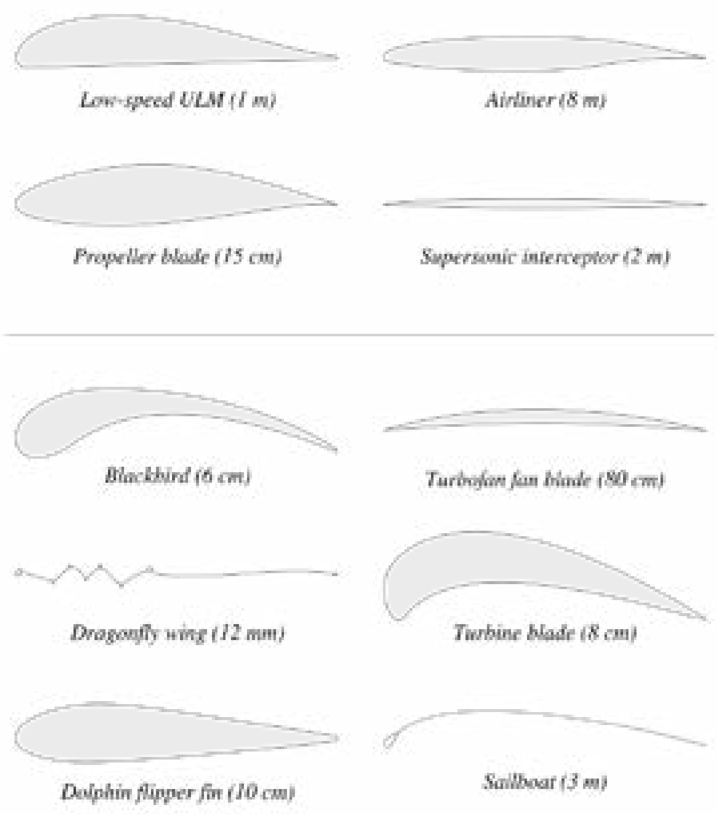

Figure 2.12: Examples of different aerofoil designs (Aerofoil Design 101)

Parts of an aerofoil

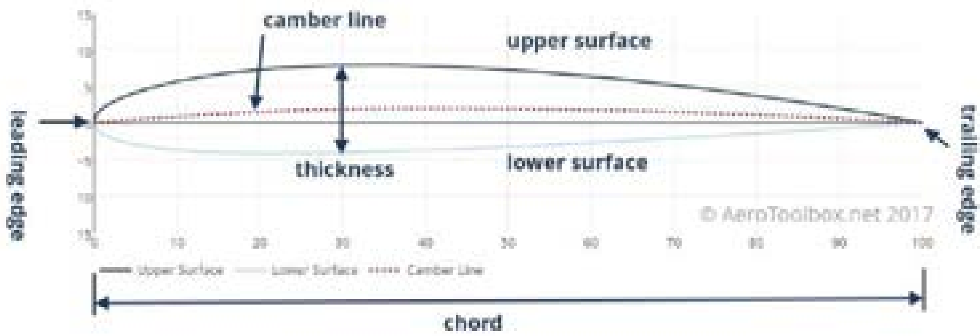

Figure 2.13: Aerofoil parts (Aerofoil Nomenclature)

The **leading edge** is the front part of the aerofoil that first contacts the incoming air, while the **trailing edge** is the rear part where the airflow exits. The **upper** and **lower** surfaces of the aerofoil connect at these edges.

The **chord** is the straight-line distance from the leading edge to the trailing edge of the aerofoil. The **thickness** refers to the maximum "depth" of the aerofoil. It is usually expressed as a percentage of the chord length. It is of particular interest during the design phase. Most aircraft wings house fuel tanks, structural members and may have hard points for carrying payloads. This makes thicker aerofoils a delight however, they create more drag at high speeds and hence are best suited for lower speed applications.

Thinner aerofoils are mostly used on high-speed aircraft since they tend to generate less drag.

Camber refers to the curvature of the aerofoil and is measured by the **asymmetry** between the upper and lower surfaces. The **camber line** (also called the mean camber line) is an imaginary line halfway between the upper and lower surfaces. A high camber means the aerofoil is more curved and generates more lift. Aerofoils with zero camber are **symmetrical** and are often found in vertical and horizontal stabilisers of the tail.

INTRODUCTION TO LIFT, HOW IT IS GENERATED AND THE FACTORS THAT AFFECT LIFT

Lift

When air flows over a solid body, it exerts some force on the body. The component of the force perpendicular to the incoming airstream is the lift force. In the case of an aircraft in flight, it acts upward and is responsible for keeping the aircraft airborne. It acts in an opposite direction to the aircraft's weight. On a fixed-wing aircraft, the wing generates the lift as the aircraft moves forward. On helicopters and other rotary-wing aircraft, lift is generated from the spinning of the rotor blades. As the blades spin, they push air downwards and by Newton's third law of motion, (every action has an equal and opposite reaction), the downward moving air gives a reaction push on the blades to create the lift.

The wings are specially designed so that air moves faster over the top of the wing than below it, creating a pressure difference. This difference in air pressure creates an upward net force that we call lift.

The diagram below of a wing's cross-section shows the aerofoil and air stream around it.

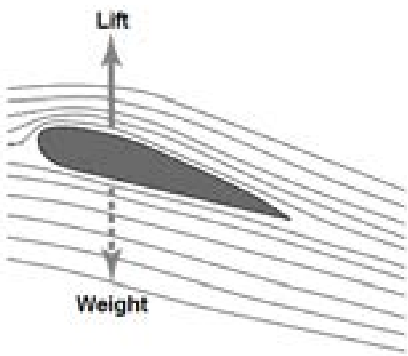

Figure 2.14: Lift acting opposite to weight (Lift Coefficient Calculator)

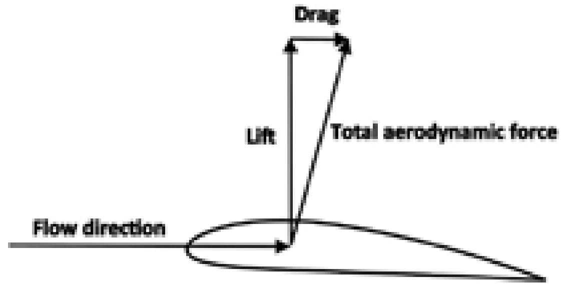

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Figure 2.15: Lift perpendicular to flow direction (How does Lift Force work?)

How Lift is Generated

As mentioned earlier, lift is generated due to differences in air pressure around an aerofoil. As air flows around a wing, the air on the upper surface moves faster than the air below it. This causes a reduction in air pressure on the upper surface and an increase in air pressure on the lower surface. This pressure difference results in a net upward force on the wing. **Figure 2.16** illustrates the pressure distribution across an aerofoil in a stream of air. In the image, colours help to show pressure differences: blue represents areas of low pressure, while red indicates areas of higher pressure.

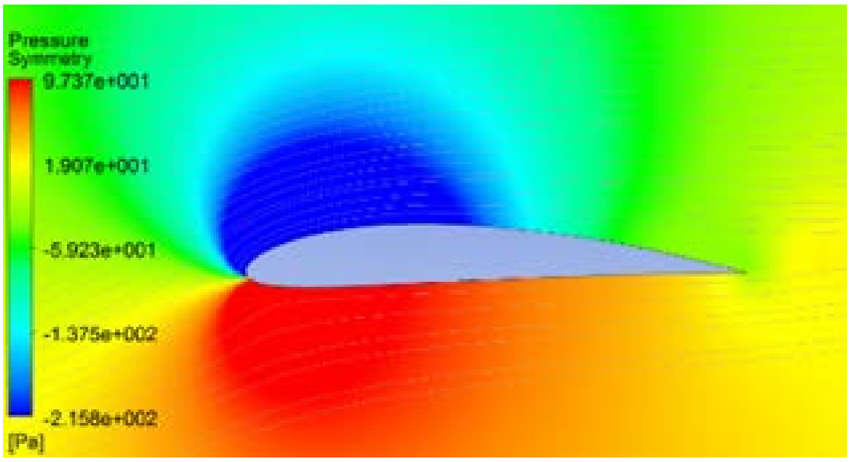


Figure 2.16: Pressure difference around an aerofoil in flight (How does Lift Force work?)

From the diagram, we can see that the air pressure above the aerofoil is lower, while the pressure below the aerofoil is higher. This difference in pressure creates an upward force – lift.

To better understand how the changes in velocity on the upper and lower surfaces of the aerofoil results in changes in air pressure, we need to look at a very important principle in fluid mechanics called Bernoulli's Principle. According to Bernoulli's Principle, when a fluid is accelerated, its pressure decreases. When air flows around the aerofoil, its speed and direction change. By Bernoulli's principle, this causes changes in pressure around the aerofoil. The aerofoils on aircraft are conveniently designed to accelerate the air on the upper surface and decelerate that on the lower surface. This result in an uneven pressure distribution that creates lift.

How Lift is Calculated

As discussed earlier, the lift force is created by the pressure distribution on the wing. When this pressure distribution is integrated over the entire wing's area and the component of the resultant parallel to the air stream is found, we get lift. However, this integration process is very complex and often involves the use of powerful computers. However, there is a simpler way to calculate lift.

First and foremost, let's consider some factors that affect the lift acting on a body. If there is no relative air stream on the wing, then no lift will be generated. Therefore, it is reasonable to think that the speed of the air stream affects the lift. Also, the density of the air affects the lift that a wing generates. Finally, the size of the wing, the aerofoil used and the orientation of the wing relative to the airstream affect the lift. Complex factors such as viscosity, and the compressibility of the air also affect lift. These are typically measured in experiments. All these factors are represented in the lift equation as follows:

where;

L is the lift force measured in Newtons (N).

C_L is the lift coefficient. The lift coefficient is a dimensionless quantity. It factors the wing orientation (angle of attack, α) and aerofoil into the lift equation.

ρ is the air density in kg/m³

v is the velocity of the airstream in m/s

S is the planform area of the wing in m²

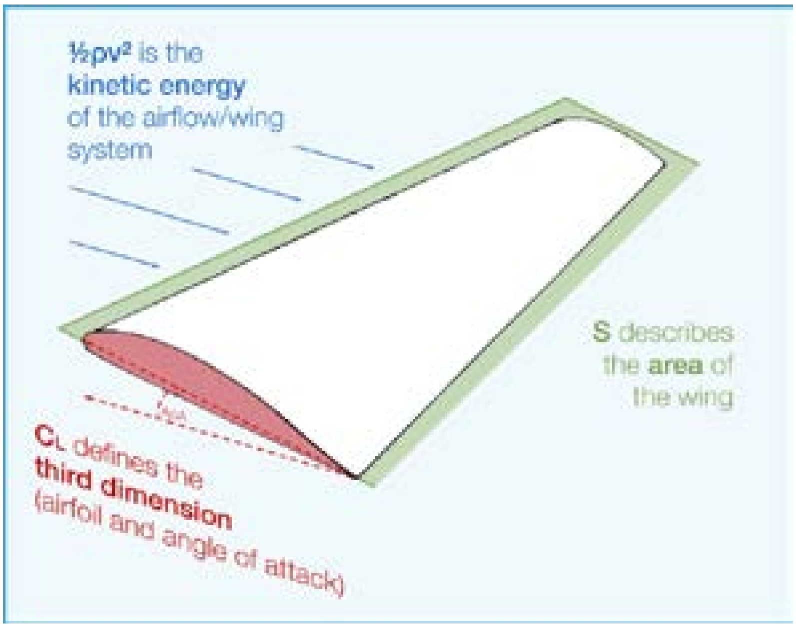


Figure 2.17: Factors affecting lift

Example 2.1

A small glider is flying at 40 m/s at an altitude of 300 m above sea level, where the air density is 1.07 kg/m³. It has a wing area of 18 m² and a lift coefficient of 1.15. Calculate the lift being generated by the glider's wings.

Solution:

Using the lift equation:

$C_L = 1.15$ (lift coefficient)

$\rho = 1.07$ kg/m³ (air density)

$v = 40$ m/s (velocity)

$S = 18$ m² (wing area)

Substituting:

1.

2. Multiply the answer by C_L and S

Answer: The lift generated by the glider's wings is approximately **17,731.2 N**.

Variation of lift coefficient with Alpha of Attack

Consider the image below of an aerofoil from a wing's cross-section. It shows the relative wind and the angle of attack (α), which is the angle between the chord line and the relative wind. Wind tunnel experiments show that the lift coefficient increases with the angle of attack until it reaches a the maximum lift coefficient.

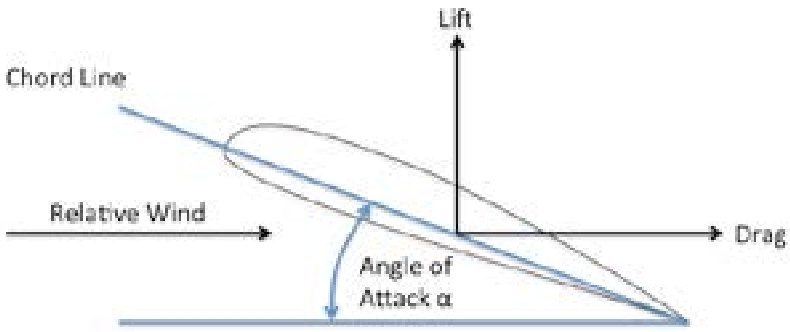


Figure 2.18: Angle of attack (aircraft design - What is the difference between Angle of Incidence (AoI) and Angle of Attack (AoA)? - Aviation Stack Exchange)

The angle of attack at which the aerofoil experiences the maximum lift coefficient is called the critical angle of attack. Any further increase in angle of attack beyond the critical angle of attack causes a sharp decrease in the lift coefficient. This is known as a stall. It is due to boundary layer separation on the upper surface. The graph below shows the variation of the lift coefficient with the angle of attack. High-lift devices can however, be used to increase the lift coefficient beyond the normal range and delaying the onset of stall, (see next sub-section for flaps and slats).

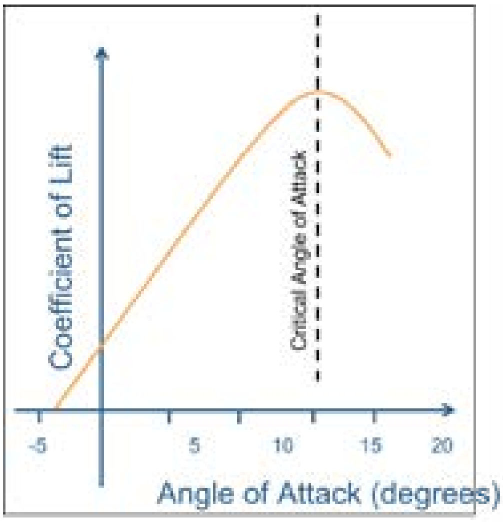


Figure 2.19: Variation of lift coefficient with angle of attack

Activity 2.2

Research and Presentation

1. Research (with videos or reading material) how lift is generated.
   - https://www.youtube.com/watch?v=6RoBo3fue4Q
   - https://www.youtube.com/watch?v=l34G_CjwECQ
   - https://www.youtube.com/watch?v=E3i_XHlVCeU
2. Your teacher will allocate you to a small group to discuss: "Describe lift as a force of flight".

   Use these prompts to guide your discussion:

   Basic Understanding of Lift:
   - *What is lift, and how does it contribute to flight?*
   - *How does lift differ from other forces acting on an aircraft, such as weight, thrust, and drag?*

   How Lift Works:
   - *What are the main factors that influence lift generation on an aircraft?*
   - *How does the angle of attack affect the amount of lift generated by an aircraft's wings?*
   - *What role does the shape of the wing (aerofoil) play in creating lift?*
   - *Can you explain how Bernoulli's principle relates to the generation of lift?*
   - *What is the relationship between airspeed and lift?*

   Lift Equation:
   - *How do the variables in the Lift equation (such as velocity, wing area, and lift coefficient) affect the lift generated?*

- *How do changes in altitude affect air density and, consequently, the lift produced by an aircraft?*

Practical Applications of Lift:

- *Why do aircraft wings have a specific design (e.g., curved on top, flat on the bottom) to maximise lift?*
- *How does an increase in velocity or wing area contribute to a higher lift coefficient?*

Limits and Challenges of Lift:

- *What is the critical angle of attack, and what happens when it's exceeded in terms of lift and stall?*
- *How does an aircraft maintain lift in turbulent or high-wind conditions?*
- *Can you describe a scenario in which lift becomes insufficient for flight?*

3.

a. From your research, identify one aircraft (from any type of aircraft) and explain how it generates lift using the theories you have already learned.

b. List some unfavourable conditions for lift for the aircraft you chose. Explain why they are unfavourable.

c. Prepare a PowerPoint presentation to present your findings to both (a) and (b) above.

4. Perform simple calculations for lift, wing area and aspect ratio.

a. Lift Calculation (Using the Lift Equation)

A light aircraft is flying at 50m/s at an altitude of 50m above sea level, where the air density is 1.225kg/m^3. It has a wing area of 20m^2 and a lift coefficient of 1.2. Calculate the lift being generated by the wings using the lift equation, $L=C_L\square 1/2\rho v^2S$.

b. Lift Calculation (Example 2)

A light stunt plane is flying at 60m/s at an altitude of 50m above sea level, where the air density is 1.225kg/m^3. It has a wing area of 25m^2 and a lift coefficient of 1.5. Calculate the lift being generated by the wings using the lift equation, $L=C_L\square 1/2\rho v^2S$.

Basic Wing Geometry

Wings are the primary lifting surfaces of an aircraft and are responsible for generating most of the lift needed to keep it in flight. The shape of the wing creates pressure differences as air flows over and under it, resulting in lift. Let us now take a closer look at the geometry and configuration of a wing.

Key parts of the wing include:

1. **Leading Edge**: The front of the wing.
2. **Trailing Edge**: The back of the wing.
3. **Chord**: The distance from the leading edge to the trailing edge.

4. **Wing Tips**: The ends of the wing.
5. **Wingspan**: The distance from one wing tip to the other.

When viewed from above, the wing's shape is known as the **planform**. For simple rectangular wings, the chord length (distance from front to back) is the same along the entire span. However, in modern aircraft, the chord length often varies, and the leading and trailing edges may be swept. The **wing area** is the total surface area within the outline of the planform, extending from the leading to trailing edges and between wing tips. **Figure 2.16** below shows the basic geometry of a wing.

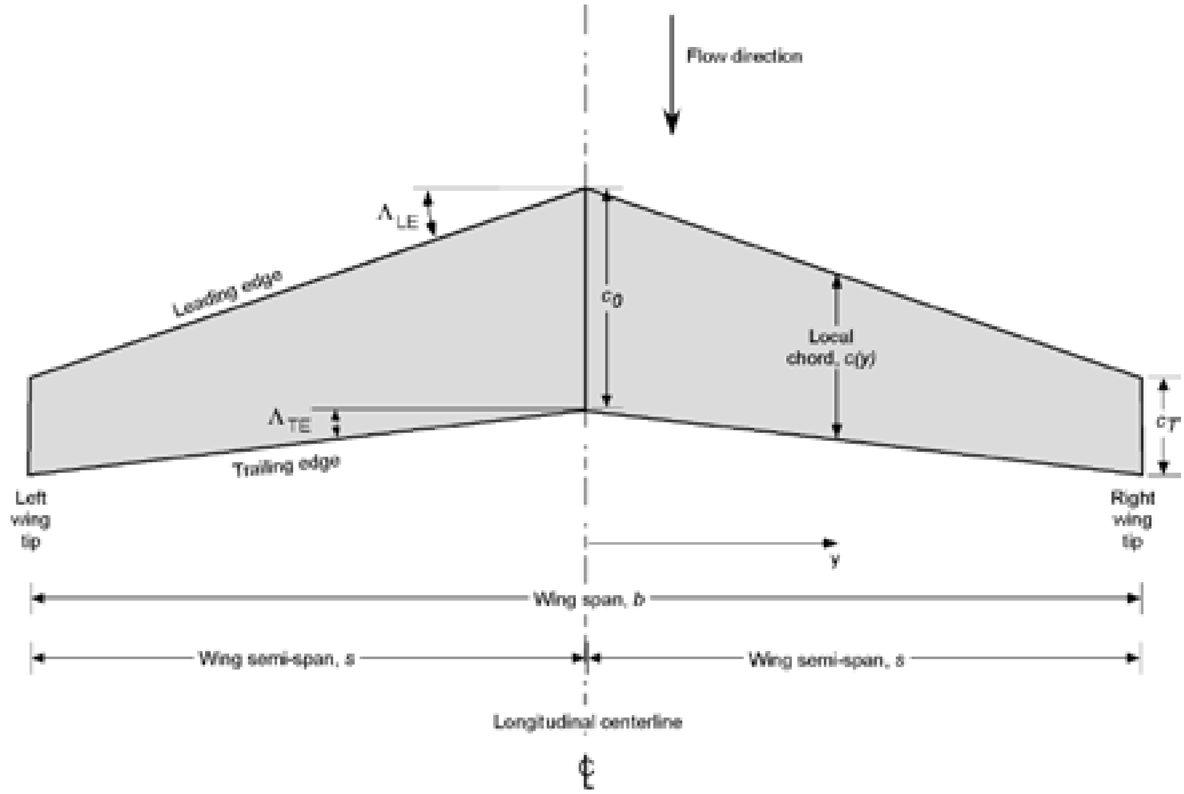


Figure 2.20: Geometric features of a wing (Wing Nomenclature)

Wingspan

The **wingspan** (or span), denoted by *b*, is the distance from one wing tip to the other. Typically, it is assumed that the right and left wings (semi-spans) are symmetrical and experience equal aerodynamic forces.

Wing chord and planform

Wings may be designed with a **linearly tapered planform**, meaning the chord length gradually decreases from the root (where the wing attaches to the fuselage) to the tip. This tapering is preferred as it balances weight and structural efficiency, reducing induced drag and improving fuel efficiency. Additionally, wing thickness often tapers toward the tip, further enhancing aerodynamic performance.

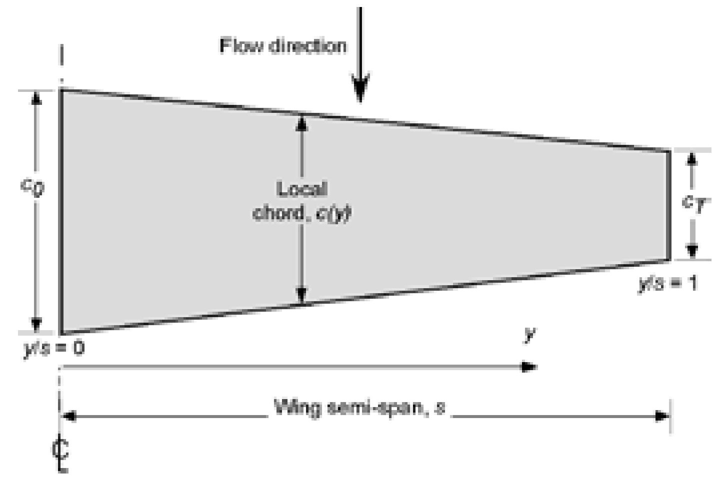


Figure 2.21: Linear planform taper

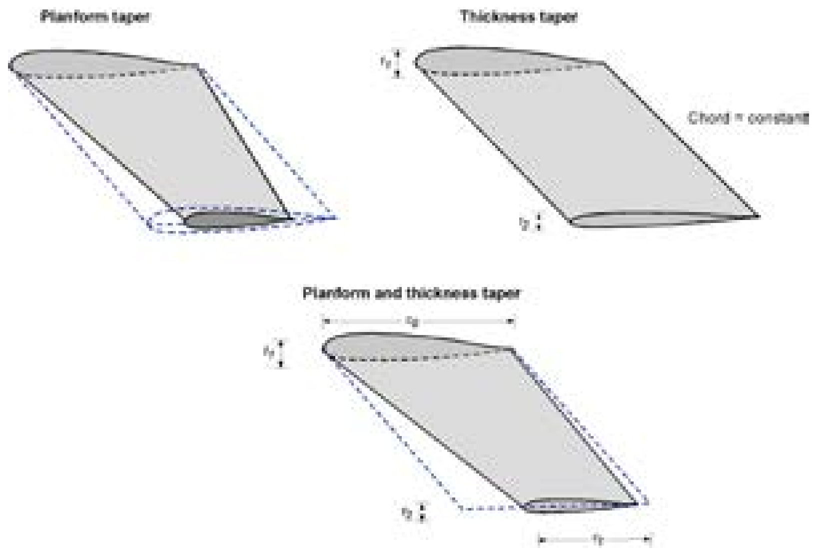


Figure 2.22: Illustration of planform and thickness taper (Wing Nomenclature)

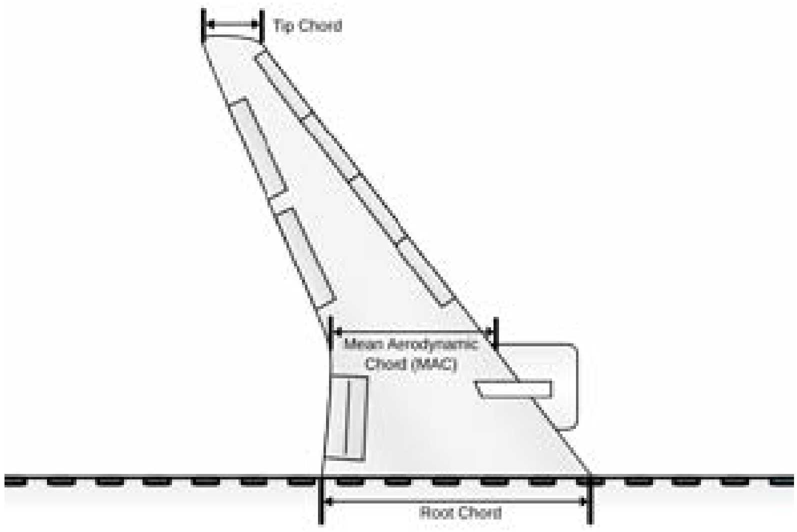


Figure 2.23: Wing Chords (Wing Nomenclature)

Sweepback Angle

Today, many aeroplanes feature **swept-back wings** (as shown in **Figure 2.24**). Wing sweepback helps reduce drag at higher speeds, particularly at a given Mach number, allowing the aircraft to require less thrust and fuel to maintain flight.

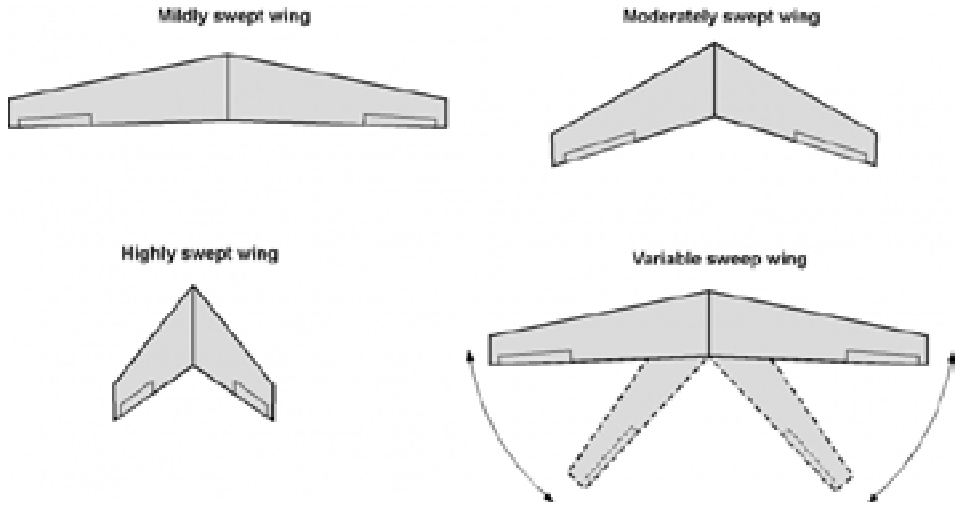


Figure 2.24: Different wing sweeps (Wing Nomenclature)

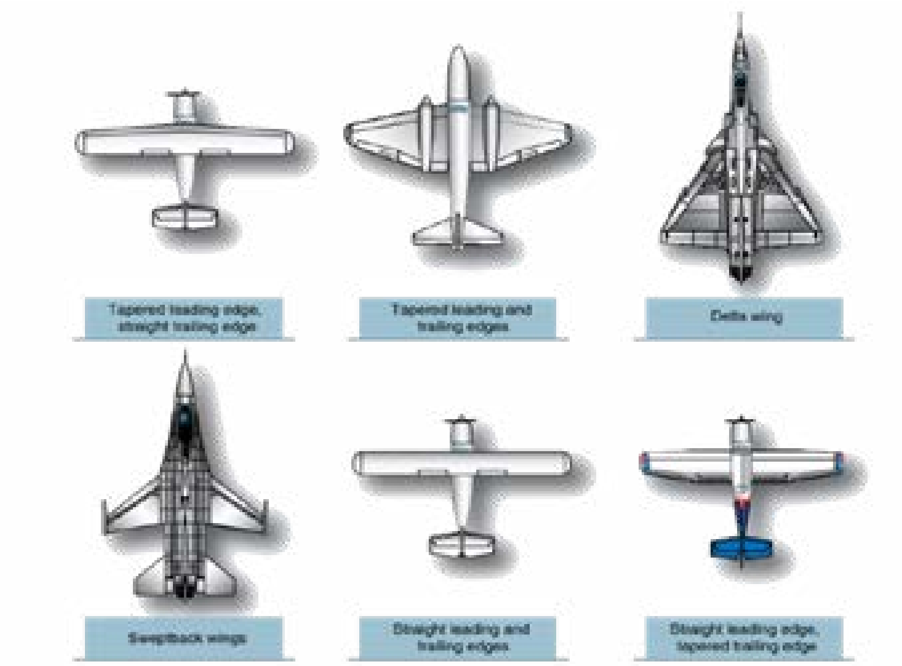


Figure 2.25: Types of wing shapes

Wing Twist

Wings may also be slightly twisted relative to their span. Wing twist is designed to help achieve the desired distribution of aerodynamic forces over the span. In practice, most wings are twisted in some form, often subtly, with the angle of the wing decreasing slightly from root to tip.

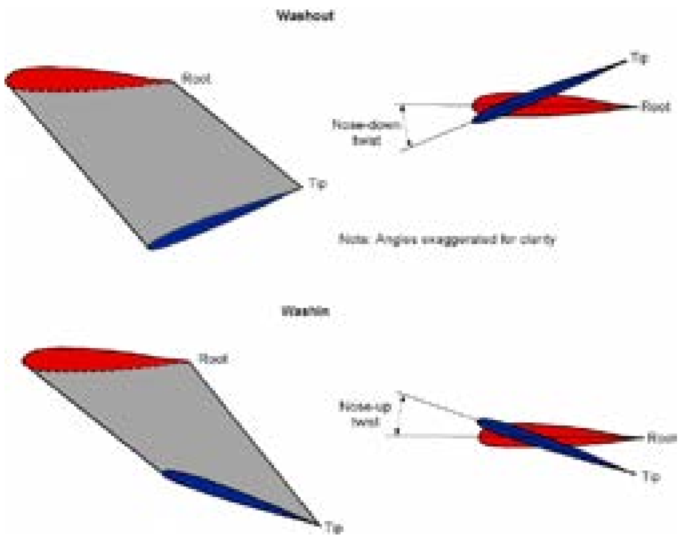


Figure 2.26: Washout and Wash-in Wing Twist ([Wing Nomenclature]())

Wing Dihedral and Anhedral Angle

The dihedral angle is the upward tilt of the wings in relation to a horizontal axis on the aircraft, as shown in **Figure 2.27** below. The main reason for using dihedral is to improve the aircraft's roll stability, which helps the aircraft stay level in flight. In larger aircraft, the horizontal tail can also have some dihedral, adding to overall stability. Some dihedral effect may also result naturally from slight bending in the wings due to structural forces during flight.

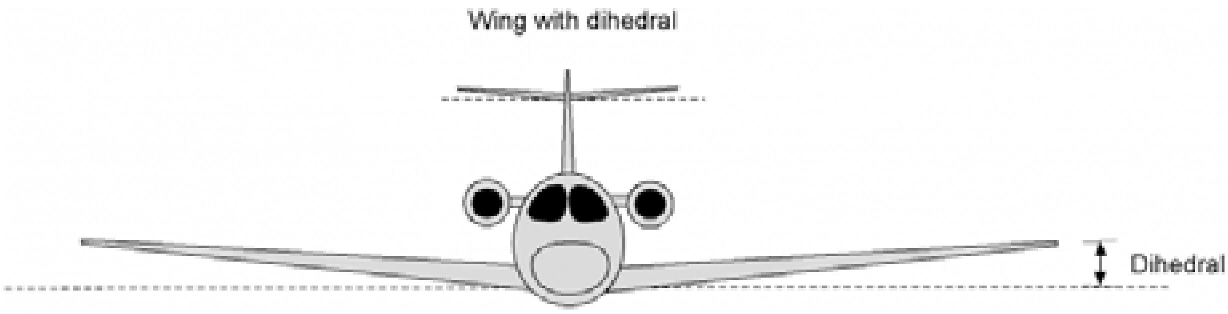


Figure 2.27: Wing with a dihedral angle(Wing Nomenclature)

Figure 2.28: Dihedral wing and tail plane of the Boeing 737-800 (Wing Nomenclature)

A downward wing angle is called anhedral. This angle is less common on aeroplanes without sweepback or high-wing designs because it decreases roll stability. However, on aeroplanes with swept-back wings, anhedral can help balance the increase in roll stability caused by the wing's sweepback angle.

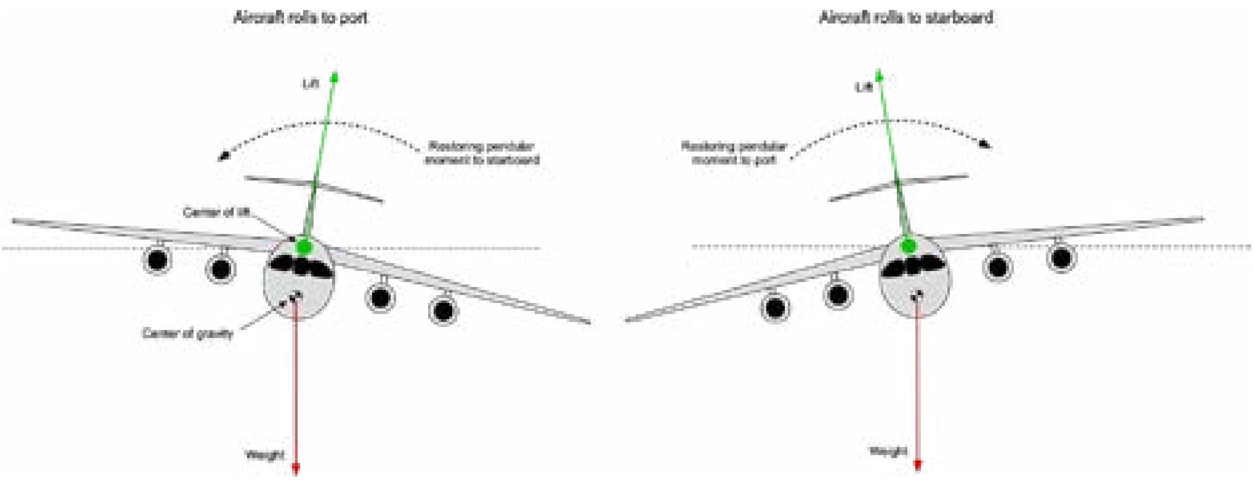


Figure 2.29: Wing with anhedral angle (Wing Nomenclature)

Figure 2.30: Military C-5 Galaxy with anhedral wing (Wing Nomenclature)

Figure 2.31: Other types of aircraft wings

How to Calculate the Wing Area

To find the area of a wing, use the following formulae:

For a rectangular wing: $S = b \times c$

Where:

S = area

b = span

c = chord length

Example 2.2

Find the area of a rectangular wing that spans 4.5 m and measures 0.38 m in chord length.

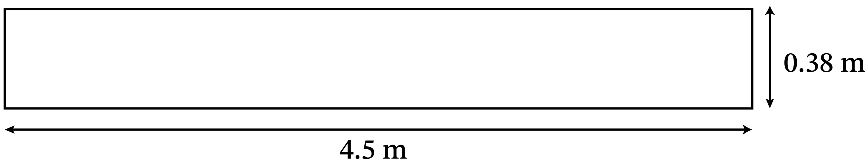


Figure 2.32: A rectangular wing

Solution:

b = 4.5 m

c = 0.38 m

Answer: The area of the wing is **1.26 m²**

For a tapered (or trapezoidal) wing:

Where:

S = area

b = span

c_t = tip chord

c_r = root chord

Example 2.3

Calculate the area of the wing below:

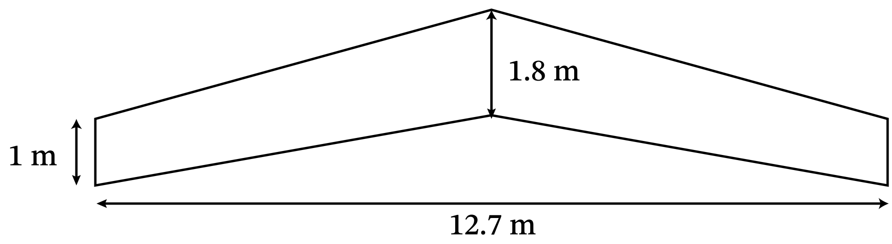


Figure 2.33: A tapered wing

Solution:

$c_r = 1m$

$ct = 1.8m$

$b = 12.7m$

For a triangular wing:

Where:

S = area

b = span

c_r = root chord

Example 2.4

Calculate the wing area of the aircraft below:

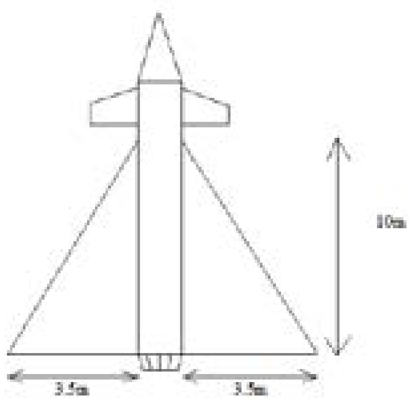


Figure 2.34: A Delta wing

Solution:

$S = 0.5 \times b \times c_r$

$S = 0.5 \times 10 \times (3.5+3.5)$

$S = 35\ m^2$

Aspect Ratio

The ratio of the length of wings to their width is called the aspect ratio. A high aspect ratio indicates long, narrow wings. A low aspect ratio indicates short, wide wings. Generally, high aspect ratio wings give slightly more lift and enable sustained, endurance flight, while low aspect ratio wings are best for swift manoeuvrability.

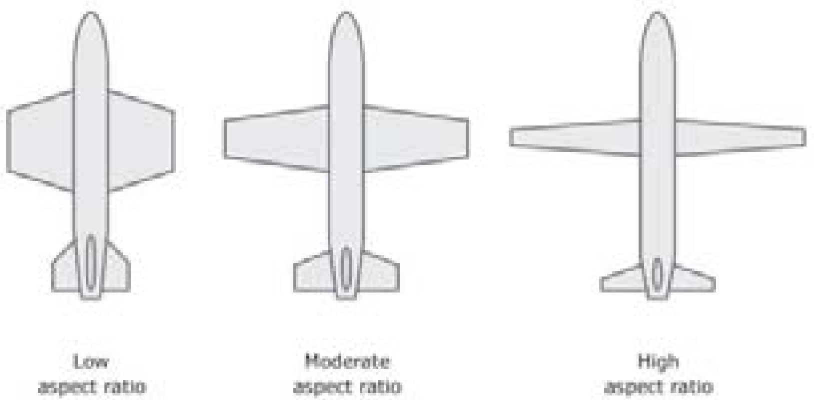


Figure 2.35: Aircraft with different aspect ratios

How to Calculate Aspect Ratio

The aspect ratio (AR) can be calculated as the square of the wingspan (b) divided by the wing area (S). This can be represented mathematically as follows:

where;

$$AR = \frac{b^2}{S}$$

AR = Aspect ratio

b = span

S = wing area

For a rectangular wing:

$S = b \times c$

where:

b = span

c = chord

This means the Aspect Ratio of a rectangular wing can be written as follows:

$$AR = \frac{b^2}{b \times c}$$

Therefore, the Aspect Ratio of a rectangular wing can be simplified as follows:

$$AR = \frac{b}{c}$$

Example 2.5

Suppose a rectangular wing has:

Wingspan (b) = 12 m

Chord Length (c) = 2 m

Then:

$$AR = \frac{12}{2}$$

Answer: The Aspect Ratio of the rectangular wing is **6.**

For a tapered wing, where the wingspan is b, the root chord is $\mathbf{c_r}$ and tip chord is $\mathbf{c_t}$

$$Wing\ Area\ (S) = \frac{1}{2}\ (c_r+c_t) \times b$$

$$S = \frac{b(c_r+c_t)}{2}$$

Recalling the equation for the Aspect Ratio:

$$AR = \frac{b_2}{S}$$

This means the Aspect Ratio of a tapered wing can be written as follows:

$$AR = \frac{b_2}{[\frac{b(c_r+c_t)}{2}]}$$

Therefore, the Aspect Ratio of a tapered wing can be simplified as follows:

$$AR = \frac{2b}{(c_r+c_t)}$$

Example 2.6

Suppose a tapered wing has:

Wingspan (b) = 15 m

Root chord (c_r) = 3 m

Tip chord (c_t) = 1.5 m

Using the simplified equation for calculating the aspect ratio:

$$AR = \frac{2(15)}{(3 + 1.5)}$$

$$AR = \frac{30}{4.5} = 6.67$$

Answer: The Aspect Ratio of the tapered wing is **6.67**.

Wing Components

Modern aircraft wings are equipped with additional components that help improve flight performance and efficiency. These components vary based on the design and purpose of the aircraft. Here, we'll cover some of the main components that enhance an aircraft's aerodynamics:

1. Drag-Reducing Devices (e.g., Winglets)
2. Control Surfaces (e.g., Ailerons)
3. High-Lift Devices (e.g., Flaps and Slats)

Drag-Reducing Devices – Winglets

Winglets are small, fin-like structures attached to the tips of aircraft wings. They are designed to reduce "induced drag," which is the drag caused by wingtip vortices (swirling air at the wing tips). These vortices create a drag force that can reduce fuel efficiency. Winglets help to minimise this effect, making the aircraft more efficient. Winglets are commonly seen on passenger aircraft.

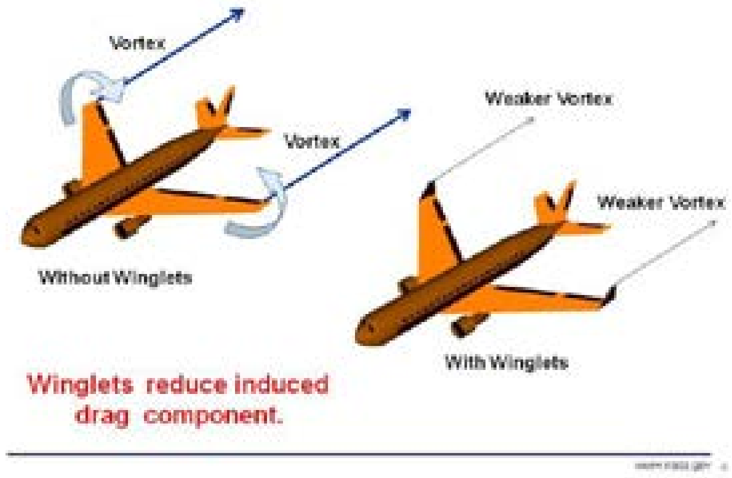


Figure 2.36: Demonstrating effects of winglets ([What is winglet device?]())

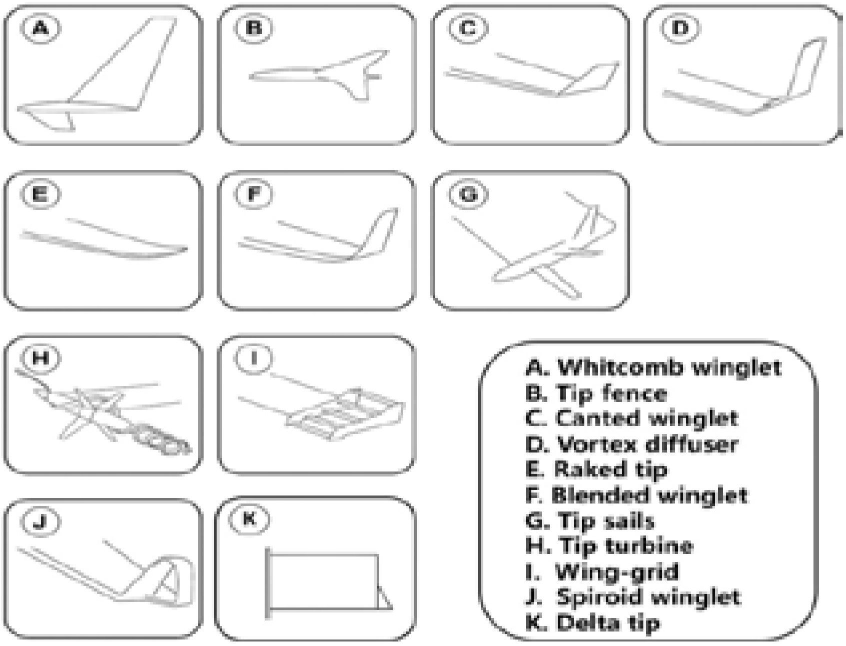


Figure 2.37: Types of winglets

Control Surfaces - Ailerons

Ailerons are movable surfaces on the trailing edges (back edges) of wings that help control the aircraft's roll—tilting it left or right along its length. When one aileron moves up, the other moves down, causing one wing to generate more lift than the other, which tilts the aircraft. Other primary control surfaces, like the elevators and rudder, are located on the tail of the aircraft.

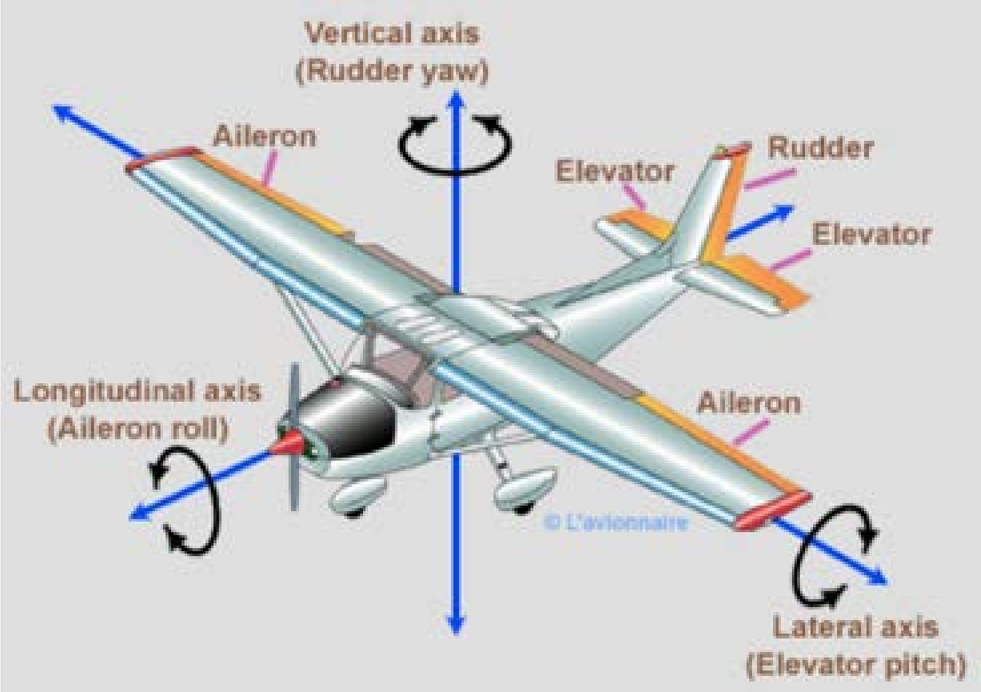


Figure 2.38: Primary control surfaces of an aircraft

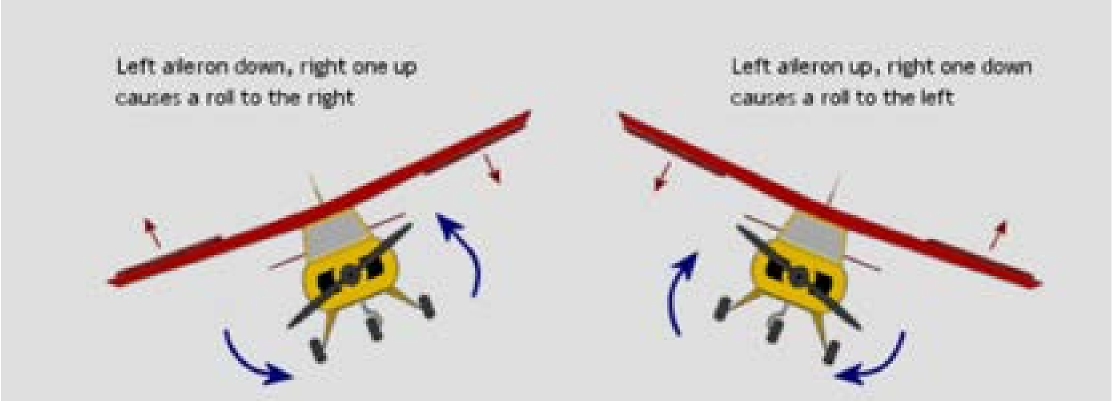


Figure 2.39: Aircraft responding to the movement of ailerons.

High-Lift Devices

High-lift devices are additional components designed to increase the amount of lift during take-off, landing, or slower-speed flight. They are often considered secondary control surfaces and are primarily used in phases when more lift is needed. Here are a few common types:

1. *Flaps*

   Flaps are attached to the trailing edge of the wing. When extended, they change the wing's shape (camber), increasing both lift and drag. This helps the aircraft achieve better lift during take-off and landing.

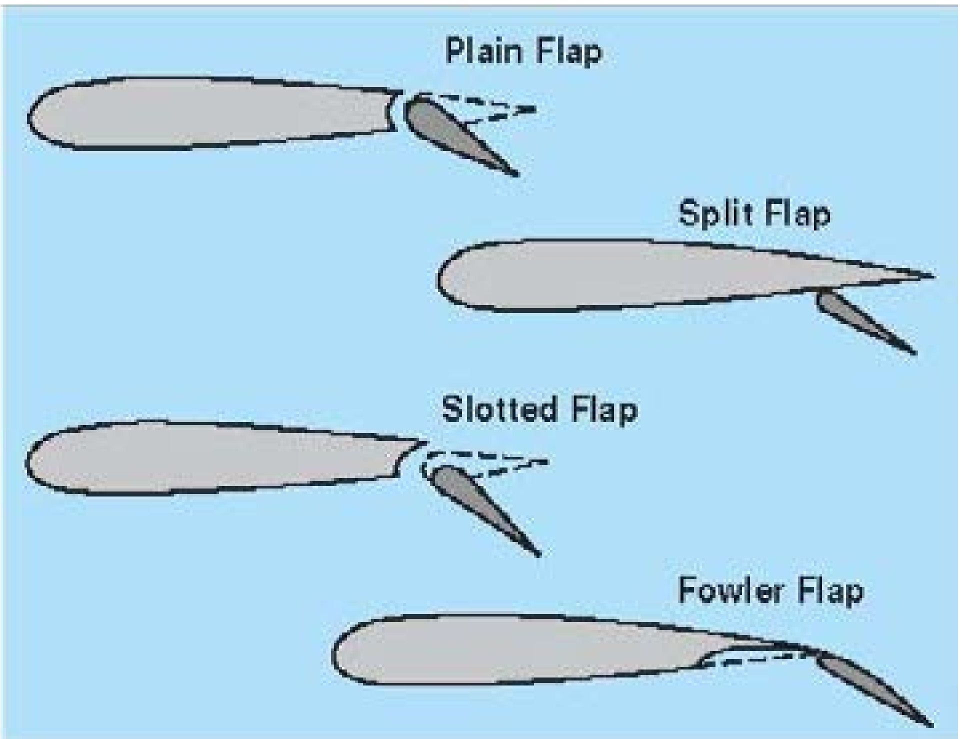


Figure 2.40: Types of flaps (Types of Flaps)

2. *Slats*

   Slats are extendable surfaces on the leading edge of some wings. Like flaps, slats are used during lower-speed phases of flight, such as take-off and landing. They work with flaps to change the wing's shape, enhancing lift

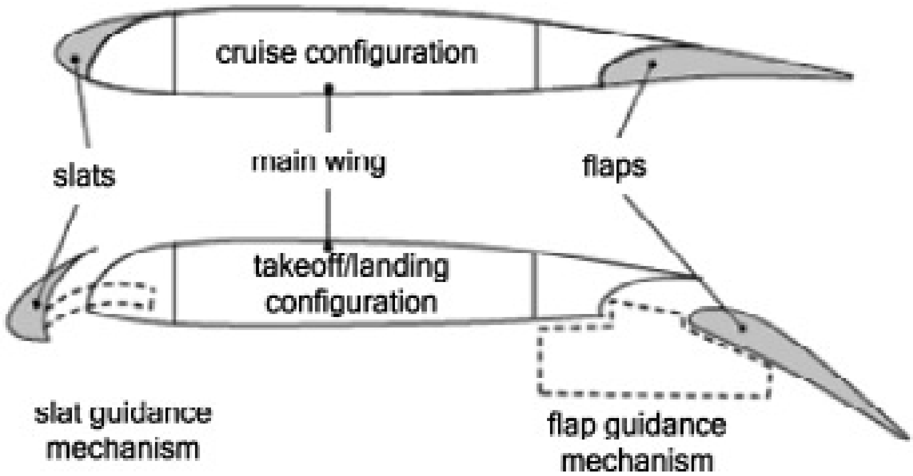


Figure 2.41: Slats and Flaps Working Together (Slats and Flaps)

3. *Krueger Flaps*

   Krueger flaps are high-lift devices attached to the leading edge of some aircraft wings. Unlike slats, they extend from the bottom of the leading edge and fold outward to increase lift by changing the camber of the wing.

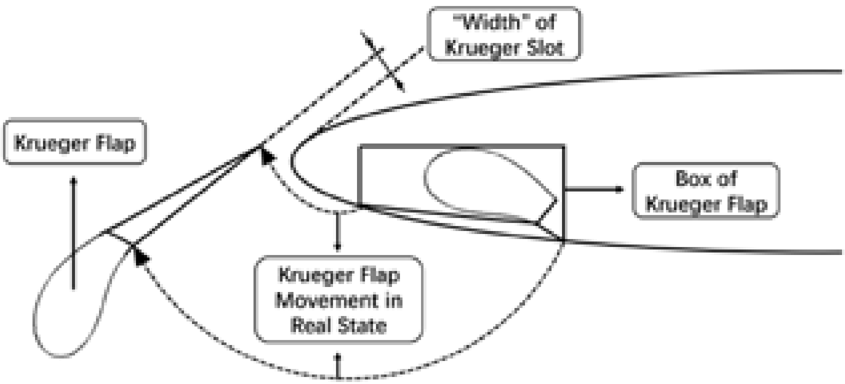


Figure 2.42: Krueger Flaps

Activity 2.3

Observing Wings for Flight

Using the following interactive website;

Observing Wings for Flight https://www.sciencelearn.org.nz/resources/3014-observing-wings-for-flight	

Activity 2.4

Exploring the Role of Wing components

1. Watch a video on how control surfaces and high-lift devices work
   - https://www.youtube.com/watch?v=G3Mf1XsQZvs
   - https://www.youtube.com/watch?v=9oVWnlO8eIw&t=13s
2. List the main control surfaces discussed in the video. Describe how each surface affects the movement of the aeroplane.

	Trailing Edge devices	Leading edge devices	Top of wing devices
What are these devices?			
How do these devices work?			
Applications (uses) of these devices			

Using a paper aeroplane or a simple cardboard model, simulate the actions of each control surface. Adjusting each control surface manually, demonstrate the movement (e.g., tilting the wings for roll).

Activity 2.5

Self-Assessment

1. Draw an aerofoil and label the following
   - **a.** Leading edge
   - **b.** Trailing edge
   - **c.** Chord
   - **d.** Camber line
   - **e.** Upper surface
   - **f.** Lower surface
2. Draw a wing and label the leading edge, trailing edge, root chord, tip chord, wingspan, and wingtip.
3. Using the following web-based simulator, observe changes in lift and drag as you adjust parameters like airspeed, air density, angle of attack, and camber; visualise the effect of changes on lift: https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/foilsimstudent/
   - **a.** What happens as you select different shapes?
   - **b.** For an aerofoil shape, what do you observe when you change the angle of attack?

DRAG

Drag is the aerodynamic force that resists an aircraft's motion through the air. It's present in all parts of the aircraft and occurs when a solid object interacts with a fluid (like air). Drag is generated due to the difference in velocity between the object and the fluid – if there's no relative motion, there's no drag.

Factors Affecting Drag

There are several factors that affect drag. These can be grouped into the following:

1. **Object Properties:** The size, shape, and surface roughness of the aircraft significantly affect drag.
2. **Air Motion:** The velocity of the air around the object influences drag, as drag increases with the square of the velocity difference between the object and air.

3. **Air Properties:** Drag depends on air density, viscosity, and compressibility, which engineers measure experimentally and account for with a drag coefficient.

The above factors are put together to form the **drag equation**. Drag can be expressed mathematically as follows:

$$D = \frac{1}{2} \rho v^2 S C_D$$

where;
D = drag

ρ = density of the air

v = velocity

S = surface area

C_D = drag coefficient

Example 2.7

An aircraft is flying steadily and level at a speed of 100m/s has a drag coefficient of 0.07 and a rectangular wing of chord 1.2m and span of 10.8m. The air density at its operating altitude is 1.08kg/m^3. Calculate the thrust that must be generated by the engine to keep the aircraft in cruise.

Solution:
From the problem statement, we know that the aircraft is in cruise. In cruise, thrust equals drag and lift equals weight.

T = D

Therefore, if we find the drag, then we get the required thrust.

$$D = \frac{1}{2} \rho v^2 S C_D$$

Speed, V = 100m/s

Drag coefficient, C_D = 0.07

Density, ρ = 1.08kg/m^3

Surface area, S = span x chord (*for a rectangular wing*)

Therefore, S = (1.2) x (10.8) = 12.96m^2

Substituting into the drag equation:

$$D = \frac{1}{2} (0.07)(100)^2 (12.69)(1.08)$$

$$T = 4898.88\ N$$

But we know that at cruise, T = D. Therefore,

$$D = 4898.88\ N$$

Reducing Drag

While drag can be useful, especially during landing where air brakes may be deployed to increase drag, engineers usually aim to minimise drag to improve fuel efficiency and increase speed capabilities when the aircraft is in flight.

Figure 2.43: Air brakes on an aircraft

Here are some strategies aircraft designers employ to reduce drag:

1. **Removing or Hiding Surface Protrusions:** Engineers minimise protrusions, like antennae or landing gear, when not in use. The use of retractable landing gear are an example of this. This prevents protrusions from sticking out into the airstream to contribute to drag. However, in the case where certain parts must protrude into the air due to design constraints, farings may be used to streamline and reduce the drag force on the component.

Figure 2.44: Faring on a non-retractable landing gear

2. **Streamlining:** Aircraft bodies are streamlined to enhance their ability to easily slice through the air. It is for this reason (see **Figure 2.45**)

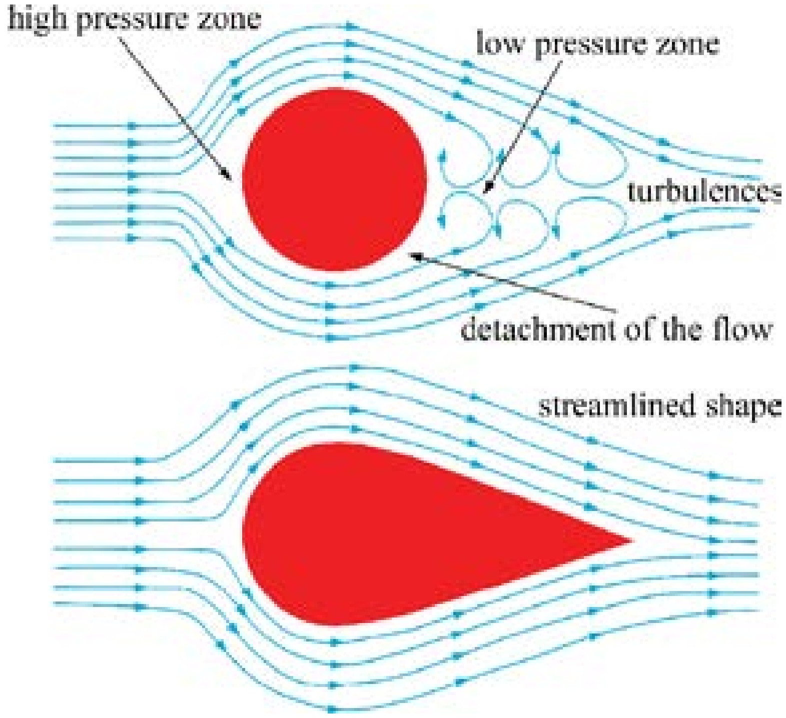


Figure 2.45: Air flow on streamlined shape versus a blunt shape.

3. **Sealing Gaps**: Gaps on aircraft (doors, canopies, control surfaces) can generate drag. Engineers ensure tight seals to prevent unnecessary drag in high-speed flight.
4. **Smoothing Surfaces**: Smooth surfaces help air flow smoothly from nose to tail, minimising resistance.

Activity 2.6

Drag

1. Watch this video - click here on skydiving. Share your views with a classmate on why they spread their arms and legs when skydiving.
2. Your teacher will allocate you to a small group of your classmates. In your group, brainstorm together to explain the concept of drag.

   Use these headings to structure your discussion:

   a. What is Drag?
   b. Types of Drag
   c. Factors Affecting Drag
   d. How Drag is Measured
   e. Impact of Drag on Aircraft Performance
   f. Reducing Drag

g. The Relationship Between Lift and Drag
h. Real-World Examples of Drag

3. Experiment to discover how drag changes with airflow speed and the surface area of an object.

Materials needed:

- *Electric fan or air blower*
- *Various pieces of cardboard (different sizes and shapes)*
- *Ruler*
- *Protractor (optional for angle variation)*
- *Notebook and pen for observations*

Instructions:

a. ***Set up the fan or blower*** on a stable surface.
b. ***Hold a piece of cardboard*** in front of the fan at a fixed distance.
c. ***Experiment with airflow speed****:*
- Start with a low speed and observe the force felt on the cardboard.
- Gradually increase the speed and note how the force changes.

d. ***Experiment with surface area****:*
- Use cardboard pieces of different sizes.
- Observe and record how the force changes with larger or smaller surfaces.

e. ***Experiment with shapes****:*
- Try using differently shaped cardboard (e.g., rectangular, circular, paper plane).
- Record the differences in drag experienced with each shape.

f. ***Optional****:* Try holding pieces of cardboard of the same size at different angles relative to the airflow and observe how this affects the force.

Observations:

Record your findings for each variable (speed, area, shape, and angle) and discuss how each affects the force felt on the cardboard.

Experiment outcomes *– using the results of your experiment, answer the following:*

a. How does increasing the speed of airflow affect the drag force on the cardboard?
b. What impact does increasing the surface area have on drag?
c. Do different shapes experience different amounts of drag at the same speed?
d. How does changing the angle of the cardboard relative to the airflow change the drag?

4. Research the contribution of the boundary layer to drag using the internet or these videos.
   - https://www.youtube.com/watch?v=GgVCTNCwfQk
   - https://www.youtube.com/watch?v=GMmNKUlXXDs

WEIGHT AND WEIGHT DISTRIBUTION

Weight is the force of gravity acting on an object, measured in Newtons (N). On Earth, weight can be calculated using:

$$Weight(W) = mass\ of\ body\ (m) \times acceleration\ due\ to\ gravity\ on\ Earth\ (g)$$

$$W = mg$$

where m is the mass of the object and g is Earth's gravitational acceleration (9.8 m/s^2). For aircraft, the total weight is the sum of all components. To reduce weight, engineers use strong but lightweight materials, balancing strength and weight for better efficiency in flight.

Weight Distribution

Weight distribution refers to how the weight or force of an object is spread across its supporting surfaces or structures. In aircraft, this is crucial for stability and balance, as uneven distribution affects the centre of gravity (CG). A well-placed CG ensures that the aircraft remains stable and controllable.

Moment of a Force

Forces may cause a body to turn about its pivot. The moment of a force refers to the turning effect of the force. It may act clockwise or anticlockwise as shown in the image below:

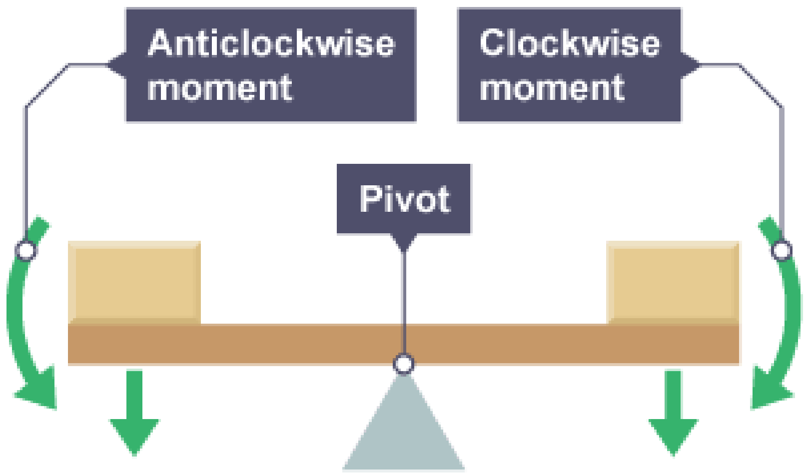


Figure 2.46: Demonstrating Clockwise and Anti-clockwise moment about a pivot

The moment of a force can be calculated by multiplying the force by its perpendicular distance from the pivot as shown in **Figure 2.45** and can be expressed as follows:

This is crucial in calculating torque on different parts of an aircraft and ensuring balanced forces during flight.

Example 2.8

1. A metre-long bar AB is subjected to the forces as shown in the diagram below. Calculate the moment about point A.

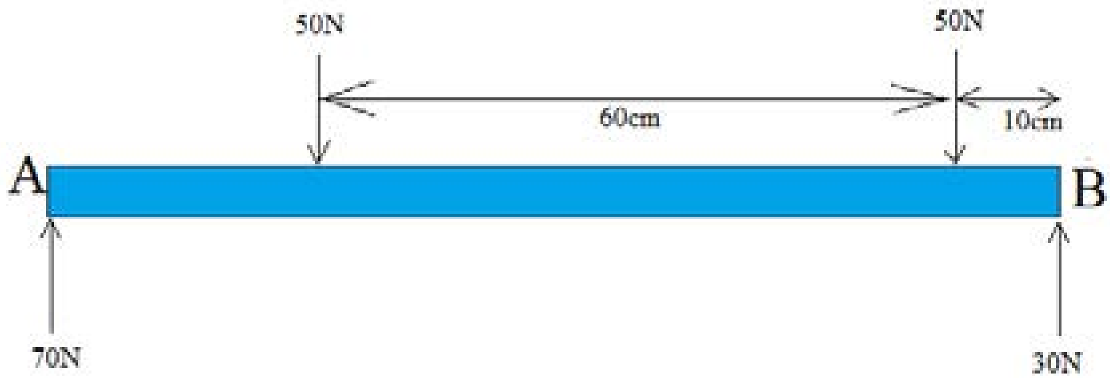


Figure 2.47: A metre-long bar

Solution:

There are four forces acting on the stick. The length of the stick is one metre. The point of interest is **A**. In order to proceed, we must pick a sign convention. Let counter-clockwise moments be positive and clockwise moments be negative. Both 50N forces will cause a clockwise moment about **A**. The 30N force will have a counterclockwise moment about A. The 70N force, however, will cause a zero moment about **A** because it acts as **A** and has zero perpendicular distance (moment arm) from **A.** Therefore, the moment about point A, designated as M_A can be found by:

$$M_A = -50(1 - 0.6 - 0.1) - 50(1 - 0.1) + 30(1)$$

$$M_A = -50(1-0.7) - 50(1-0.1) + 30(1)$$
$$M_A = -50(0.3) - 50(0.9) + 30(1)$$
$$M_A = -15 - 45 + 30$$
$$M_A = -60 + 30$$
$$M_A = -30\ N.m$$

This implies that the moment about point **A** is 30N.m and acts in a clockwise direction because it is negative.

Centre of Gravity

The centre of gravity (CG) is the average location of an object's weight. It's an imaginary point where the total weight can be considered concentrated. The CG plays a key role in aircraft design, as it affects stability and control. An aircraft's CG must fall within certain limits to ensure safe operation; if it's too far forward or aft, it can lead to handling issues or even accidents.

The CG is typically calculated by balancing all moments on the aircraft, taking into account both weight and position of each component.

Example 2.9

The aircraft below has a total weight of 18110 N. The engine weighs 12000N, the fuel weighs 1600N and it carries a payload of 3200N. It uses a 24V battery pack which weighs 1100N.

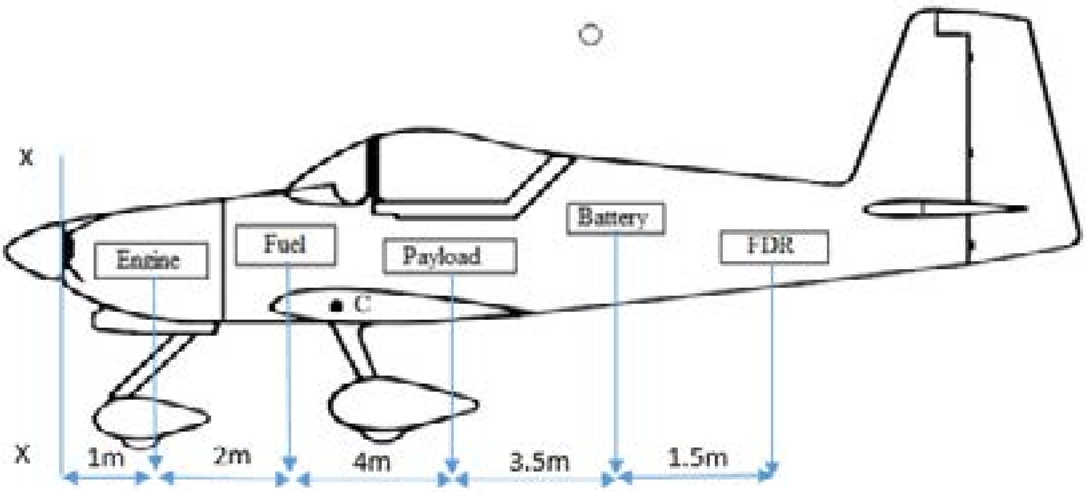


Figure 2.48: Aircraft

a. What is the mass of the flight data recorder (FDR)? [Take $g = 9.81 m/s^2$]

Solution:

The total weight is **18110N**. This means the sum of all weights on the aircraft should equal 18110N. Therefore, we can write the following:

$$18110 = 12000 + 1600 + 3200 + 1100 + W_{FDR}$$
$$18110 = 17900 + W_{FDR}$$
$$W_{FDR} = 18110 - 17900$$
$$W_{FDR} = 210N$$

But remember the question was to find the mass of the FDR, not weight. We know that weight is a product of mass and acceleration due to gravity.

Hence,

$$m_{FDR} = \frac{W_{FDR}}{g}$$

Therefore,

$$m_{FDR} = \frac{210}{9.81}$$

$$m_{FDR} = 21.41\ kg$$

Activity 2.7

Understanding Weight Distribution and Centre of Gravity

Materials Needed:

- A metre rule
- A pivot (e.g., an eraser or block)
- weights (e.g., coins or small weights)
- Digital scale

Instructions:

1. **Form Groups:** Join a small group made up of 3-4 of your classmates (including you).
2. **Balance the Metre Rule:** Place the metre rule horizontally on the pivot and find the balance point (where it doesn't tip to either side). Mark this point.
3. **Measure and Record Weights:** Using a digital scale, measure the masses of all the weights at your disposal. Calculate the weight of these items. Take acceleration due to gravity, g, as $9.81 m/s^2$. Record your results.
4. **Add Weights:** Attach a measured weight to one end of the metre rule. Adjust the pivot position to find the new balance point.
5. **Repeat Experiment:** Add weights in different configurations, noting the balance point each time. Try this process about four times.

6. **Observe and Discuss:** Discuss as a group how the added weights affect the balance and what this implies about weight distribution and centre of gravity.

Questions to Consider:

a. Where does the pivot need to be to balance different weight configurations?

b. How does the distance of weight from the pivot affect balance?

c. What does this tell you about the role of balance in aircraft design?

EXTENDED READING

- Aerofoil Nomenclature
- *Fundamentals of aerodynamics by John Anderson Jr.*

Review Questions

1. An aircraft is cruising with a speed **v**. If it increases its speed to **2v**, by how much does the lift increase considering all other factors equal?

2. A fixed-wing UAV cruising at a speed of 45m/s has a drag coefficient of 0.03 and a tapered wing of 60cm root chord, 30cm tip chord and wingspan of 8m. It is flying at an altitude where the air density is 0.95kg/m3.
   a. Calculate the drag on the aircraft.
   b. If the lift coefficient is 0.9, calculate the lift.

3. When the angle of attack reaches beyond the critical angle of attack, a wing stalls. Why?

SECTION 3

PROPULSION SYSTEMS

CORE CONCEPTS IN AEROSPACE ENGINEERING

Aerodynamics and Propulsion

INTRODUCTION

Welcome to Section 3! In this section we'll focus on systems that propel aerospace vehicles. There are different technologies, suited to different applications, and we take a look at them, beginning with electric propulsion, piston engines, gas turbine engines and finally rocket propulsion. We will learn about their principles of operation and as well, learn how to compute the thrust produced by gas turbine and rocket engines.

Key Ideas

- Almost all Aerospace propulsion systems employ mechanisms that make use of Newton's third law of motion (law of action and reaction) to create thrust.
- Air-breathing engines are limited to operations in the Earth's atmosphere while rockets are capable of operating in space.

PRINCIPLES OF AEROSPACE PROPULSION AND PROPELLER-BASED PROPULSION SYSTEMS (ELECTRICAL AND INTERNAL COMBUSTION)

Introduction to Propulsion

In the previous section, we discussed how lift is created when air moves relative to the wing. In order to create the relative airflow, the aircraft must move forward. Aircraft use different types of systems to move through the air and create this relative airflow. These systems are known as propulsion systems.

The word "propulsion" comes from two Latin words: "pro," meaning forwards, and "pellere," meaning to push or drive. So, propulsion means moving a body forwards. A propulsion system is made up of parts that work together to push or drive an object forward. The forwards force produced by propulsion systems is called thrust. To understand how thrust is created, it is important to first look at Newton's Laws of Motion.

Newton's Laws of Motion

Newton's first law states that "an object will be in a state of rest or move in a straight line at a constant speed unless an unbalanced force acts on it." This is called the **law of inertia**. In simple terms, it means that an object at rest will not start moving unless an outside force pushes or pulls it. Similarly, an object in motion will keep moving at the same speed in the same direction—without speeding up, slowing down, turning, or stopping—until an unbalanced force acts on it.

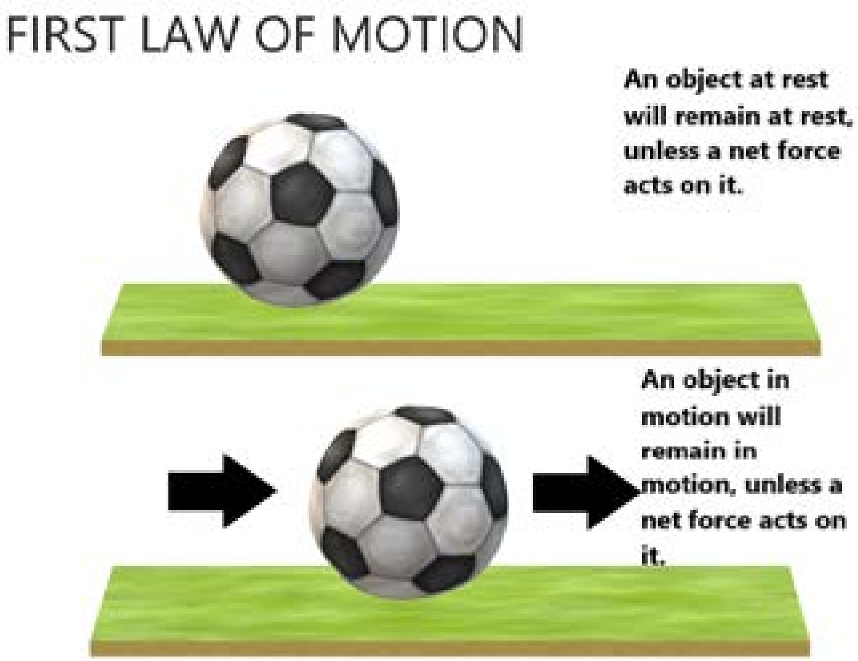


Figure 3.1: A ball demonstrating Newtons first law of motion. Newton's First Law of Motion - Formula, Examples, and Applications (geeksforgeeks.org)

Let's look at the above picture. In the upper part, the ball is seen to be in a state of rest. There is no external force in action, and there is no motion. This is a commonly observable case. It would be unlikely for a stationary ball to move by itself without any external force acting on it. Now, consider the bottom part of the image where the ball has been kicked and is in motion in a straight line. Newton's first law of motion claims the ball must continue moving along a straight line unless an external force acts on it. This may initially seem contrary to what is observed physically, which is that when a ball is kicked it gradually slows down and eventually comes to a stop. This is because there is an external force acting on the ball once it begins moving. This external force is friction. The friction between the ball and the ground acts to oppose the motion of the ball, slowing it down to an eventual stop. Were it not for friction, the ball would keep on moving.

1. Newton's second law states that "**the rate of change of momentum of a body is directly proportional to the net force acting on the body and it acts in the direction of the net force**".
2. Momentum is the product of a body's mass and velocity. It is a vector quantity like velocity. It is mathematically expressed as;

$$P = mv$$

Where P is momentum, m is the mass of the object and v is the velocity.

Momentum tells us how hard it would be to stop an object that's moving. A heavier object moving fast has more momentum than a lighter object moving slowly. This means that the more momentum an object has, the more force would be needed to bring it to a stop or change its direction.

Newton's second law simply means a net force acting on a body changes its momentum and the change in momentum acts in the direction of the net force. It can be expressed as

$$P = \frac{mass * change\ in\ velocity}{change\ in\ time} = \frac{m\Delta v}{\Delta t}$$

However,

$$acceleration\ (a) = \frac{\Delta v}{t}$$

, therefore; $F = ma$

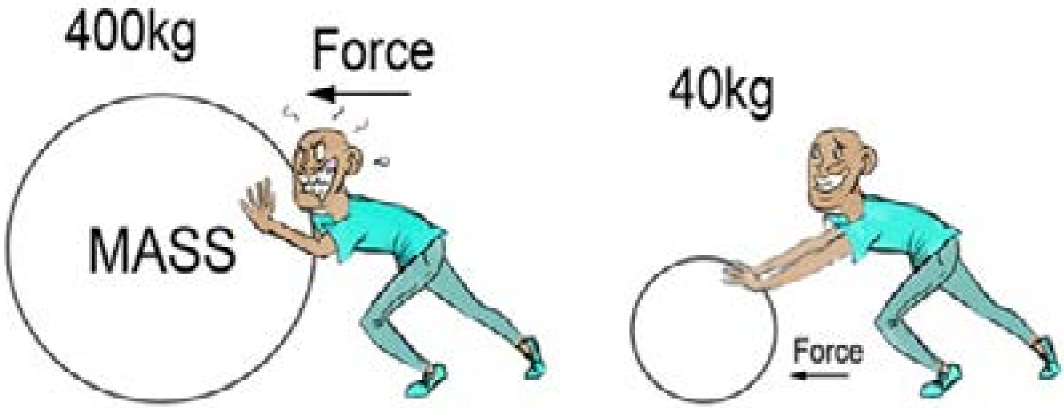


Figure 3.2: Moving two boulders of different masses

In the image above, a man is trying to push a boulder in two different cases. In the first case, the boulder has a mass of 400 kg, and in the second, it weighs 40 kg. Since the first boulder is much heavier, the man has to apply more force to get it moving (that is, to change its velocity from zero to some other value). In contrast, in the second case, he needs to use less force to accelerate the lighter boulder, as it weighs much less than the first one.

Newton's third law states that "for every action, there is an equal and opposite reaction." This means that when two objects interact, they apply forces to each other that are equal in strength but opposite in direction. For example, imagine a brick resting on a table. The brick pushes down on the table with a force due to its weight. At the same time, the table pushes up on the brick with a force equal to the brick's weight, keeping it balanced. This is known as the law of action and reaction (Newton's third law of motion).

Let's look at a more interesting example. When you swim, you move the water backwards, because of this, the water pushes you forward.

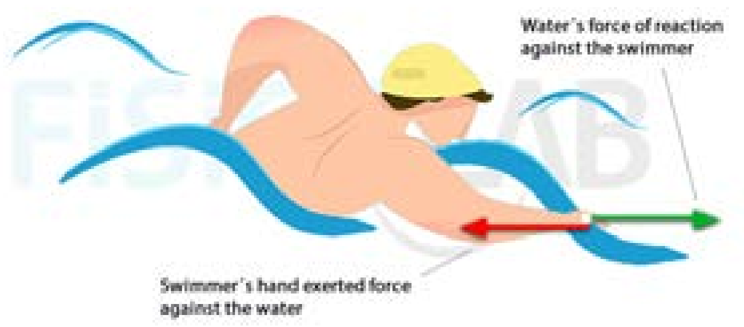


Figure 3.3: Action and reaction of swimming Newton´s Third Law

Newton's third law is fundamental to the operation of most aerospace propulsion systems. They employ some "action and reaction" mechanisms to generate thrust. These types of engines are called reaction engines.

Types of Aerospace Propulsion Systems

There are four main types of propulsion systems used on aerospace vehicles. They are:

1. Electrical Propulsion
2. Piston Engine
3. Gas Turbine Engine
4. Rockets

Electrical Propulsion

Electric propulsion in aircraft is an emerging technology that replaces conventional jet or piston engines with electric motors powered by batteries, fuel cells, or other forms of electric energy. This shift has the potential to significantly reduce emissions, noise, and reliance on fossil fuels in aviation, making it a promising option for a more sustainable future in air travel.

Figure 3.4: Elektra Trainer Aircraft. Elektra Trainer - Elektra Solar

In electric propulsion, electric motors drive the aircraft's propellers or fans to generate thrust, similar to traditional engines. However, unlike conventional engines that rely on fuel combustion, electric motors convert electrical energy directly into mechanical energy. The motors are typically powered by onboard batteries, which store electrical energy, or by fuel cells, which generate electricity through chemical reactions, usually using hydrogen and oxygen.

Key Components of Electric Propulsion Systems

1. **Electric Motors:** Electric motors provide the thrust needed to propel the aircraft. They are designed to be highly efficient, lightweight, and simpler in design compared with combustion engines. They may be brushed or brushless however most manufacturers design electric aircraft around brushless motors because they are more efficient.

Figure 3.5: Electric Motor

2. **Battery Packs or Fuel Cells:** Batteries store energy needed for flight, with lithium-ion batteries currently being the most common. Fuel cells are also being explored as a longer-range option, converting hydrogen into electricity. They may also be fitted with battery management systems to monitor and manage performance.

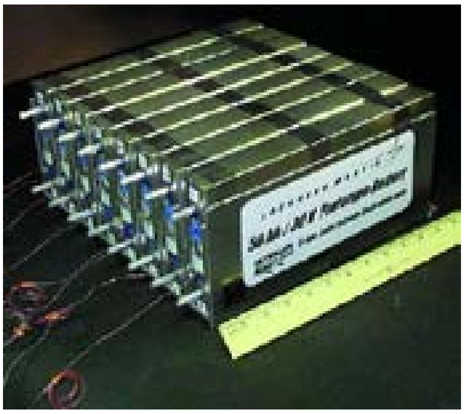


Figure 3.6: Lithium Polymer battery pack File. NASA Lithium Ion Polymer Battery.jpg - Wikipedia

3. **Power Electronics:** These control the distribution of power from batteries or fuel cells to the motors, managing the energy flow and ensuring efficient operation.

4. **Thermal Management Systems:** Electric propulsion generates heat, which must be managed to prevent overheating of the motors and batteries. Cooling systems are used to ensure optimal performance and safety.

Advantages of Electric Propulsion

1. **Environmental Benefits:** Electric propulsion reduces or eliminates greenhouse gas emissions associated with conventional aviation. Especially with renewable energy sources charging the batteries, electric propulsion has the potential for nearly zero operational emissions.

2. **Noise Reduction:** Electric motors operate much more quietly than jet engines, reducing noise pollution around airports and in urban areas.

3. **Lower Operating Costs:** Electric propulsion systems are usually cheaper to implement, especially on small UAVs. They require little maintenance to keep them operational, and so have much lower operational costs.

Challenges in Electric Propulsion for Aircraft

1. **Battery Limitations:** Current battery technology limits the range and payload of electric aircraft. Battery charge energy density (the amount of energy stored per unit of weight) is a critical factor, and advancements are needed to make long-haul electric flights feasible.

2. **Infrastructure Needs:** Airports would need to adapt to support electric aircraft, requiring charging stations, hydrogen refuelling for fuel cells, and maintenance facilities specialised in electric systems.

3. **Weight and Efficiency:** Batteries and fuel cells add weight, and aircraft design needs to balance the weight of the energy source with the aircraft's range and payload requirements. In aircraft that use combustion fuel, the fuel is burnt to produce thrust. This means that the weight of the aircraft reduces throughout the journey, thereby improving efficiency and range. This is not the case for electric propulsion systems, which rely on batteries.

The Future of Electric Aviation

While commercial electric airliners may still be years away, smaller electric planes are already in operation, primarily in short-haul and training flights. Electric propulsion holds the promise of reshaping the aviation industry, with long-term goals focused on achieving carbon-neutral flights and reducing the environmental impact of air travel. With continued advancements in battery technology, fuel cells, and efficient electric motors, electric propulsion may soon power a new generation of sustainable aircraft.

Piston Engine Propulsion System

Piston engines, also known as reciprocating engines, have been a primary power source for aircraft since the early days of aviation. These engines, which operate by burning fuel to drive pistons within cylinders, are commonly found in smaller general aviation aircraft, helicopters, and older aircraft types. These engines are similar to those found in cars with some modifications to make them more suitable for flight. Some of these modifications include the use of two ignition systems for redundancy and safety and air cooling in place of liquid cooling to reduce weight, though some piston engines may still use liquid cooling.

Although jet engines dominate commercial and military aviation today, piston engines remain vital for smaller planes and helicopters due to their simplicity, reliability, and cost-effectiveness. There are various configurations of piston engines. The arrangement of pistons could be inline, horizontal, V-type or radial.

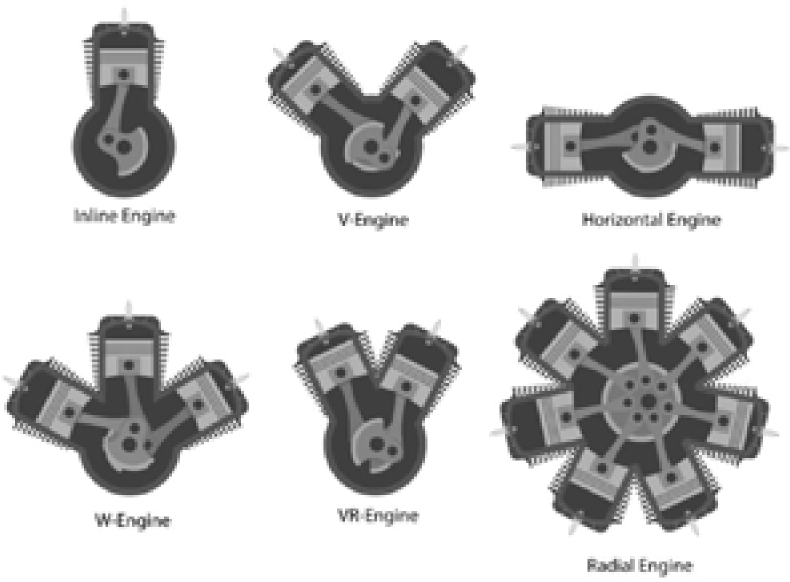


Figure 3.7: Piston Engine Configurations. Straight and V-Type Engines Explained - saVRee

Components of Aircraft Piston Engines

There are components of various types of piston engine. Let us now look at some prominent and generic parts found on piston engines.

1. **Cylinder and Piston:** Cylinders house the pistons and provide the chamber for fuel combustion. Most piston engines have multiple cylinders arranged in rows or radial patterns.
2. **Crankshaft:** The crankshaft converts the up-and-down motion of the pistons into rotational motion to drive the propeller.
3. **Spark Plugs:** Spark plugs ignite the fuel-air mixture in each cylinder, a key part of the combustion process.
4. **Carburettor or Fuel Injection System:** The carburettor mixes fuel and air before sending it to the cylinders, while fuel injection systems deliver fuel directly to each cylinder for improved efficiency.
5. **Cooling System:** Piston engines may use either air cooling, with airflow directed over the engine, or liquid cooling, with coolant circulating around the engine parts. Effective cooling is essential to prevent overheating and maintain performance.

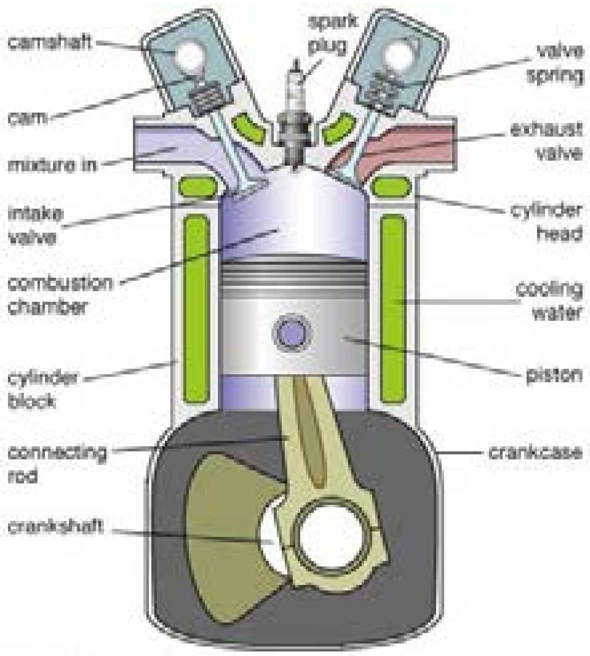


Figure 3.8: Parts of a Piston Engine: Piston Engine Parts

How Piston Engines Work

Piston engines operate through a series of repetitive actions in their cylinders, converting fuel combustion into mechanical energy to drive the propeller and create thrust. The process typically follows these steps:

1. **Intake**: The inlet valve opens, and the piston moves down, creating a vacuum that pulls a fuel-air mixture into the cylinder.

2. **Compression**: With both inlet and outlet valves closed, the piston moves up, compressing the air to prepare it for combustion. Fuel is added to the compressed air.
3. **Power/Combustion:** Still with both valves closed, the spark plug ignites the compressed mixture, causing a small explosion that forces the piston downward.
4. **Exhaust:** The outlet valve now opens, and the piston moves back up to expel exhaust gases out of the cylinder. Then the cycle begins again.

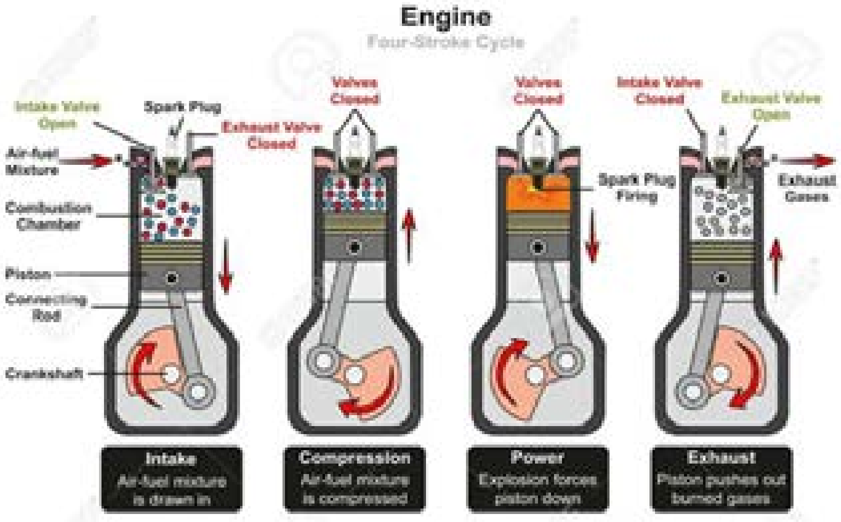


Figure 3.9: Operation of a four-stroke engine (Power Stroke Diagram)

This sequence, called the four-stroke cycle, repeats multiple times per second, creating rotational motion in the engine's crankshaft. The crankshaft, in turn, drives a gearbox to which a propeller is coupled, producing thrust that moves the aircraft forward. There are some piston engines that operate in only two cycles and hence are called two-stroke engines. They are mostly used on small unmanned aircraft.

Advantages of Piston Engines in Aircraft

1. **Simplicity and Cost:** Piston engines have a relatively straightforward design and are cheaper to produce and maintain than gas turbine engines. This makes them ideal for small aircraft and general aviation.
2. **Fuel Efficiency:** Compared with jet engines, piston engines are generally more fuel-efficient at lower speeds and altitudes, where small planes typically operate. This efficiency reduces operational costs.
3. **Reliability:** With fewer moving parts and well-established technology, piston engines have a strong reputation for reliability, especially in the typical flight conditions for small aircraft.
4. **Ease of Maintenance:** Piston engines are simpler to maintain, with many standardised parts and accessible components, making them manageable for private aircraft owners and operators.

Limitations of Piston Engines

1. **Power and Speed Constraints:** Piston engines are limited in power and are less suitable for high-speed or high-altitude flight, where jet engines excel. This restricts them mainly to small and medium-sized aircraft that operate at lower altitudes.
2. **Cooling Challenges:** Air-cooled piston engines can overheat, especially in warmer climates or during long flights at full power. While liquid cooling is sometimes used, it adds weight and complexity.
3. **Vibration and Noise:** Piston engines generate significant vibration and noise, which can impact passenger comfort and require additional soundproofing measures.
4. **Limited High-Altitude Performance:** As is the case with air-breathing engines in general, piston engines typically lose efficiency at high altitudes due to reduced air density, though turbocharging can help counteract this to some extent.

Propellers

Propellers are a key component of many aircraft, used to convert the rotational power generated by an engine into forward thrust. Found on both piston-engine and turboprop aircraft, propellers operate by pushing air backwards, creating a reaction that moves the aircraft forwards. While modern commercial airliners primarily use jet engines, propellers are still essential for small planes, general aviation, and various types of specialised aircraft due to their efficiency at lower speeds and altitudes. They are also heavily used on drones and eVTOLs.

How Propellers Generate Thrust

Propellers work on the principle of aerodynamic lift, similar to how an aeroplane's wings generate lift. Each propeller blade is essentially a small wing, with an aerofoil shape designed to create a pressure difference as it moves through the air. When the engine turns the propeller, the blades cut through the air, creating lower pressure in front of the propeller and higher pressure behind it. This difference in pressure generates thrust, propelling the aircraft forwards.

Propeller blades are usually twisted along their length to maintain efficiency, as the blade tips move faster than the sections closer to the hub. This twist allows each part of the blade to generate optimal lift, maximising thrust while minimising drag.

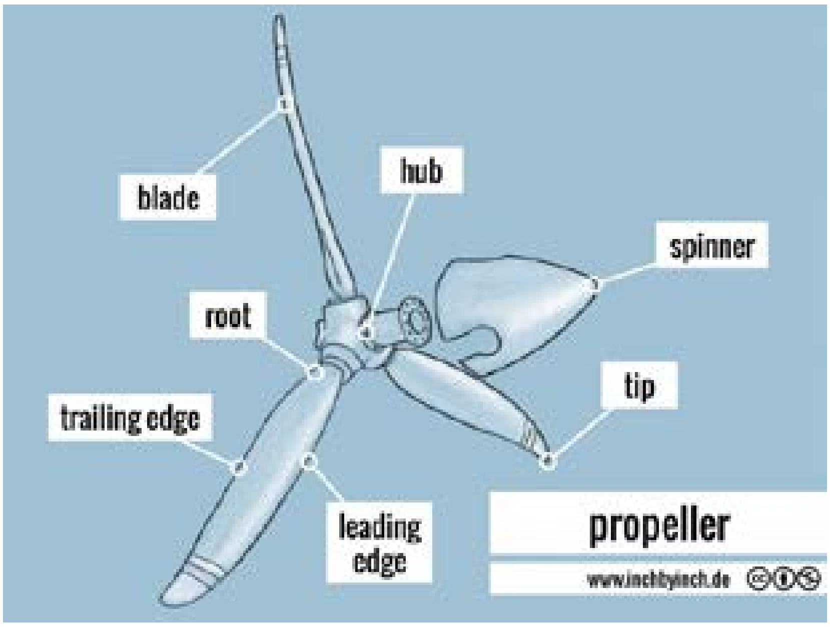


Figure 3.10: Parts of a propeller [INCH - Technical English | pictorial: propeller (inchbyinch.de)]

Types of Propellers

There are many types of propellers used in the aircraft industry. Below are the two most common ones:

1. **Fixed-Pitch Propellers:**

   Fixed-pitch propellers have blades set at a fixed angle and cannot be adjusted in flight. These are typically used in light aircraft and are simpler and more affordable, but they limit performance flexibility as they cannot adjust to changing flight conditions.

Figure 3.11: A fixed-pitch propeller [Wooden Airplane Propeller Vintage - Free photo on Pixabay - Pixabay]

2. **Variable-Pitch Propellers:**
Variable-pitch propellers allow the pilot to adjust the angle of the blades, optimising thrust for different phases of flight. This makes them more versatile and efficient across a range of speeds and altitudes. The blades can be rotated into a position parallel to the flow. This is useful if the engine fails as it minimises the drag on the aircraft, allowing it to glide more efficiently. Some may also be rotated to generate reverse thrust. This helps in slowing down the aircraft during landing and may be used to move the aircraft in reverse while on the ground.

Figure 3.12: Variable pitch propeller
Effect Of Propeller Pitch Angle On An Airplane Thrust. | Science Fair Project Ideas (sciencefairprojects.in)

Activity 3.1

Demonstrating Newton's Third Law of Motion

1. Using a balloon, demonstrate Newton's third law of motion (law of action and reaction).
   Material needed: *Balloon*
   Procedure:
   a. *Inflate the balloon.*
   b. *Hold the inflated balloon at the neck to keep the air in.*
   c. *Release the neck of the inflated balloon.*

   What was your observation, and how can it be explained using Newton's third law?
2. Organise yourselves into small groups of no more than 5. In your groups, visit Animated Engines - Four stroke, where you can see an animation of a piston engine and read more about its operation. You may slow down the animation

to better observe the cycles of operation. Try to identify the parts of the engine. What is the name of the mechanism that operates the valves?

3. Research the Internet to discover how a propeller spins to generate thrust. Outline this process in your notebooks.
4. Perform a thrust test with a brushless DC motor in the laboratory. The objective of this exercise is to test the thrust produced by a Brushless DC (BLDC) motor under varying conditions in a laboratory setting.

Required Materials:

- *Brushless DC Motor (BLDC Motor)*
- *Electronic Speed Controller (ESC)*
- *Power supply (adequate voltage for motor)*
- *Thrust measurement apparatus (Force sensor or thrust stand)*
- *Tachometer (optional for RPM measurement)*
- *Speed control interface (e.g., a potentiometer or computer interface)*
- *Wattmeter (to measure power consumption)*
- *Multimeter (to measure voltage and current)*
- *Mounting hardware (for securing the motor and thrust sensor)*
- *Personal protective equipment (PPE: Safety glasses, gloves, etc.)*
- *Data logging equipment (e.g., computer or notebook for recording data)*

Procedure

a. ***Set up the testing apparatus***:
   i. *Mount and secure the BLDC motor to the thrust stand or the testing rig using appropriate mounting hardware. Ensure that the motor is positioned so that it can produce thrust along a single axis.*
   ii. *Connect the motor to the motor controller (ESC) and verify the motor wiring according to the motor's specifications (e.g., 3-phase connections for a 3-phase BLDC motor).*
   iii. *Secure the battery in a position such that potential vibrations from the motor do not move it. Ensure the battery is disconnected until you are ready to begin the test.*

b. ***Install the thrust measurement system***:
   i. *Mount the force sensor in line with the motor's axis to measure the thrust produced. The force sensor should be oriented to measure linear force (along the axis of thrust).*
   ii. *Ensure that the force sensor is calibrated according to the manufacturer's instructions.*
   iii. *If using a tachometer, install it to measure the motor's rotational speed (RPM).*

c. ***Initial Power and Speed Check***:
   i. *Power up the setup by connecting the battery. Ensure the motor controller is receiving the correct signals from the speed control interface (e.g.,*

receiver or flight controller).

ii. *Start the motor at a low speed (e.g., 10-20% of maximum speed).*

iii. *Look out for the direction in which the motor is spinning. Ensure it is spinning in the desired direction, whether clockwise or counterclockwise. If it is spinning opposite to the intended direction, switch any two of the three connections between the ESC and BLDC motor. For a brushed motor, a simple reversal of polarity should do the trick.*

iv. *Now, disconnect the battery again and mount your propeller. The propeller should be properly inspected for cracks and deformities. It should be mounted firmly in conformity with the spin direction of the motor and the intended thrust direction. Ensure that the propeller is free to move unobstructed. Also remove surrounding loose material to prevent them from being sucked into the airstream of the propeller when it begins to spin.*

d. *Perform the thrust test*:

i. *Reconnect the power to the setup.*

ii. *Gradually increase the speed of the BLDC motor in increments (e.g., 10%, 25%, 50%, 75%, and 100% of maximum speed).*

iii. *At each speed increment, record the thrust measured by the force sensor. Ensure that the motor reaches a stable speed before recording the thrust data.*

iv. *Record the motor's speed (RPM), thrust (in Newtons), and power consumption (voltage and current) at each increment.*

v. *If available, log data using a computer interface or data logging equipment to automate the process of collecting readings.*

e. *Data Collection*:

i. *Record the following at each speed setting:*
- *Speed of the motor (RPM)*
- *Thrust produced (N)*
- *Voltage and current (V, A)*
- *Power*

ii. *Ensure that measurements are recorded at a steady state for each speed increment. This can be achieved by waiting for about 10-20 seconds after each throttle increment before recording. This is to give the system enough time to reach a steady state.* ***Table 3.1*** *can be used as a template for recoding the data.*

Table 3.1: Data recording template

Motor type	*Propeller*	*Throttle (%)*	*Voltage (V)*	*Current (A)*	*Power (kW)*	*Thrust (g)*	*RPM*
		10					
		20					
		25					
		30					
		40					
		50					
		60					
		70					
		80					
		90					
		100					

f. ***Data Analysis****:*

Plot graphs to analyse how thrust changes with respect to motor speed and power input.

i. Plot ***Thrust vs. Motor Speed (RPM)****.*
ii. Plot ***Thrust vs. Power Input (W)****.*

g. ***Repeat Test (if necessary)****: Repeat the test under different conditions, such as varying the voltage supplied to the motor or testing with different propellers to observe changes in thrust generated*

Safety Considerations

- ***Wear appropriate safety gear****: Safety glasses, gloves, and closed-toe shoes must be worn.*
- ***Use fresh propellers****: It is safe to use new propellers when conducting a thrust test as they are less likely to have cracks and imperfections which may cause incidents when spinning.*
- ***Check for overheating****: Monitor the motor, controller, and power supply for signs of overheating. If any component becomes excessively hot, stop the test immediately.*
- ***Secure components****: Ensure that all parts are firmly secured, especially the motor and thrust measurement system, to avoid any accidental disconnections or loose components during testing.*

- ***Work in a well-ventilated area****: BLDC motors and controllers may generate heat during operation, so proper ventilation is necessary.*

Questions for Group Discussion

1. How does the thrust vary with changes in the motor's speed?
2. Was there a point where the motor's thrust began to plateau despite an increase in speed? What might explain this behaviour?
3. How could you improve the setup for more accurate thrust measurements in future tests?
4. Were there vibrations in the setup? What could have caused these vibrations, and how can they be reduced?

PRINCIPLES AND TYPES OF PROPULSION

Gas Turbine Propulsion Systems

Gas turbine engines are a type of internal combustion engine widely used in aviation to power commercial airliners, military aircraft, helicopters, and even some small aircraft. These engines are known for their ability to generate a large amount of thrust and operate efficiently at high speeds and altitudes, making them ideal for fast and long-distance flight. Gas turbines are classified into several types, including turbojets, turbofans, turboprops, and turboshafts, each with unique characteristics tailored to different kinds of aircraft and flight requirements.

How Gas Turbine Engines Work

A gas turbine engine works by drawing in air, compressing it, mixing it with fuel, and igniting the mixture to produce high-temperature, high-pressure gases. These gases then expand and accelerate as they exit the engine, generating thrust. This process is broken down into four main stages:

1. **Intake:** Air is drawn into the engine through the intake, where it is directed into the compressor.
2. **Compression:** The compressor, typically a series of rotating blades, compresses the incoming air, increasing its pressure. Compressing the air also raises its temperature and density, preparing it for combustion.
3. **Combustion:** The compressed air is mixed with fuel in the combustion chamber and ignited. This combustion generates a high-energy, high-pressure gas which expands rapidly.
4. **Exhaust/Turbine:** The hot gases pass through a turbine, which extracts some of the energy to drive the compressor and other engine components. After passing the turbine, the remaining high-speed gases exit the engine through the nozzle.

The exit of the high-speed gas through the nozzle produces a reaction force on the engine. This reaction force is the thrust.

This continuous cycle of intake, compression, combustion, and exhaust allows the engine to produce a steady stream of thrust.

Types of Gas Turbine Engines

1. **Turbojet:** Air enters the engine through guide vanes. The air then goes on to the compressor stages, where it is compressed. The compressors could be axial or radial. Once compressed, the air enters the combustion chamber. In the combustion chamber, fuel is added to the compressed air and ignited. The gases expand rapidly, turning the turbine and exiting the propelling nozzle at high speed to create thrust. Turbojets are the most basic form of jet engines. They are more efficient at high speeds and altitudes but are relatively noisy and less fuel-efficient at lower speeds. They are typically used in high-speed military aircraft and older jet models.

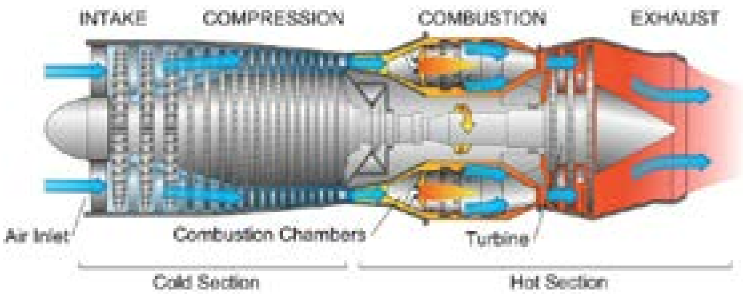


Figure 3.13: A turbojet engine

2. **Turbofan:** The most common type of gas turbine engine in commercial aviation, a turbofan, features a large fan at the front that pushes additional air around the engine core. This bypassed air (not used in combustion) generates extra thrust and reduces noise. Turbofans are more fuel-efficient than turbojets and are well-suited for commercial airliners and transport aircraft. Even some military jets use turbofan engines.

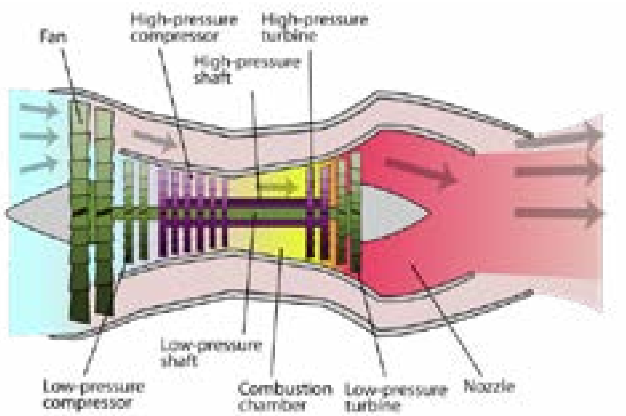


Figure 3.14: Turbofan engine with bypass
[How does a jet engine work? (innovationdiscoveries.space)]

3. **Turboprop:** Turboprop engines use a gas turbine to drive a propeller rather than relying solely on exhaust gases for thrust. It combines the jet engine's efficiency at high speeds with the propeller's efficiency at low to medium speeds, making it ideal for regional and military aircraft. They are highly efficient at lower speeds and altitudes, making them ideal for regional and commuter aircraft. The propeller generates most of the thrust, while the exhaust gases provide some additional thrust.

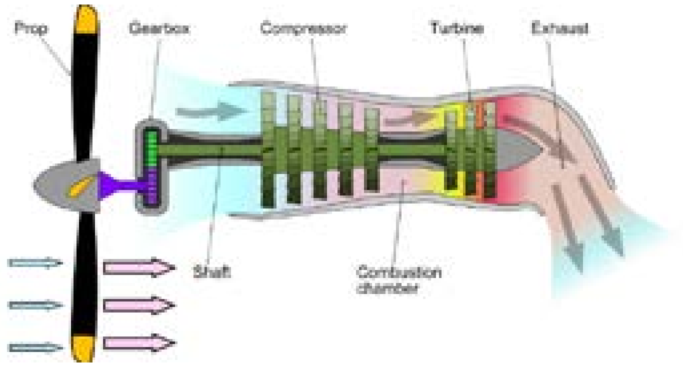


Figure 3.15: Turboprop engine

4. **Turboshaft:** Turboshaft engines are similar to turboprops but are designed to transfer nearly all of the turbine's power to a shaft rather than generating thrust through exhaust. These engines are commonly used in helicopters. Air is drawn into the engine through the intake. The compressor compresses the incoming air, increasing its pressure and temperature. The compressed air is mixed with fuel in the combustion chamber and ignited, resulting in a high-energy airflow. The high-energy airflow passes through the turbines. The first set of turbines (gas generator turbines) drives the compressor, while the second set (power turbines) drives the output shaft. The shaft connected to the power turbine delivers mechanical power to drive rotors, propellers, marine vessels or generators. The remaining gases are expelled through the exhaust.

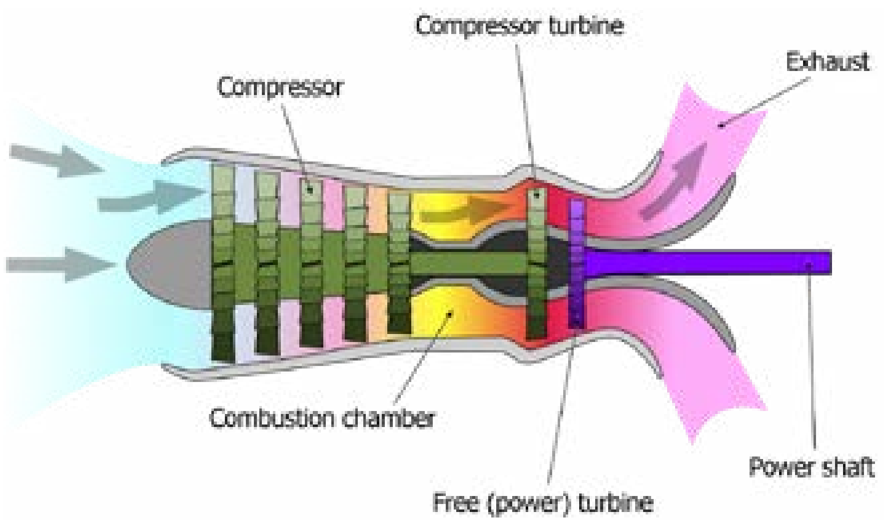


Figure 3.16: Turboshaft engine

Benefits of Using Gas Turbine Engines

1. **High Thrust-to-Weight Ratio:** Gas turbines produce large amounts of thrust relative to their weight, making them efficient for high-speed, long-distance travel.
2. **Efficiency at High Altitudes:** Gas turbines perform well at high altitudes, where the air is thin. This makes them suitable for commercial and military aircraft flying at cruising altitudes.
3. **Smooth and Continuous Power:** Unlike piston engines, gas turbines operate with fewer vibrations, providing a smoother flight experience for passengers.
4. **Long Service Life:** With fewer moving parts and less internal friction, gas turbines are highly durable and reliable, which is ideal for frequent, long-haul flights.
5. **Adaptability:** Gas turbines can be adapted for various applications, from powering commercial jets and helicopters to generating electricity in power plants.

Challenges Associated with Gas Turbine Engines

1. **Fuel Consumption at Low Speeds:** Gas turbines are less fuel-efficient at low speeds, which is why they are primarily used for high-speed and long-distance flights rather than short-haul trips.
2. **High Operating Costs:** The materials and precision manufacturing required for gas turbines make them expensive to produce and maintain, contributing to higher operating costs.
3. **Noise:** While turbofan engines are quieter than turbojets, gas turbines generally produce significant noise. Advanced technology has reduced this in recent years, but noise still remains a challenge in some applications.
4. **Complex Maintenance:** Gas turbines require highly skilled maintenance to ensure their reliability and safety. Components are exposed to extreme temperatures and pressures, so regular inspections are necessary.

Research is ongoing to make gas turbine engines more fuel-efficient and environmentally friendly. Advancements include the development of geared turbofans, which allow the fan and turbine to operate at optimal speeds independently, further improving efficiency. Hybrid-electric systems, which combine gas turbines with electric motors, are also being explored to reduce emissions and fuel consumption. Additionally, hydrogen fuel and biofuels are being investigated as alternatives to conventional jet fuel. With continued innovation, gas turbine engines will remain a core technology in aviation, contributing to the drive toward a more sustainable and efficient air travel.

Rocket Propulsion

Rocket propulsion is a method of generating thrust by expelling mass (exhaust gases) at high speed in the opposite direction of desired movement, enabling rockets to propel forward according to Newton's third law of motion: "For every action, there is an equal and opposite reaction." Rocket propulsion systems are unique because they carry both the fuel (for energy) and the oxidiser (for combustion), allowing them to operate in the vacuum of space where there is no atmospheric oxygen. This feature sets rocket propulsion apart from other forms of propulsion, like gas turbine and piston engines, which rely on atmospheric air for combustion.

How Rocket Propulsion Works

Rocket engines operate by combining fuel and an oxidiser within a combustion chamber, where they react to produce extremely hot, high-pressure gases. These gases are then forced through a nozzle, accelerating them to high speeds and producing thrust in the opposite direction.

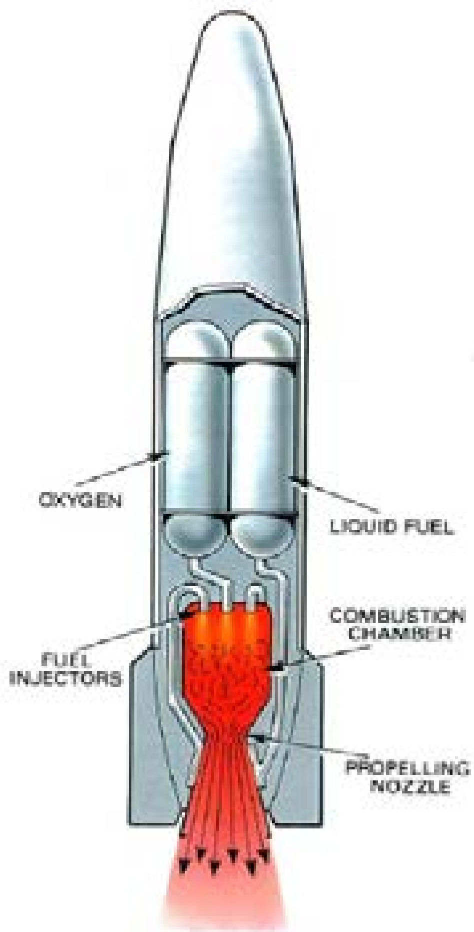


Figure 3.17: A rocket. Maybach: 1 Basic Mechanics

The key parts of a rocket engine are:

1. **Propellant Tanks:** These tanks store both the fuel and oxidiser. Depending on the rocket, the propellants can be in liquid or solid form.
2. **Combustion Chamber:** This is where the fuel and oxidiser mix and burn, creating hot gases that build up pressure. The ignition system is used to ignite the fuel and oxidiser.
3. **Nozzle:** The nozzle accelerates the expanding gases as they exit the engine, focusing them to produce a high-speed jet that generates thrust.

Types of Rocket Propulsion

1. **Chemical Rocket Engines:** These engines are the most commonly used in space applications and launch vehicles. Chemical rockets can use either liquid or solid propellants. In these solid rocket engines, the fuel and oxidiser are mixed into a solid form. Once ignited, solid rocket fuel burns until the propellant is exhausted. They are simple, reliable, and provide high thrust but lack the ability to be throttled or turned off mid-flight. Liquid Rocket Engines use liquid fuel and oxidiser stored in separate tanks, which are pumped into the combustion chamber. Liquid rockets offer control over thrust levels, allowing throttling, restarting, and shutting down, making them ideal for precise space manoeuvres.
2. **Electric Propulsion:** Electric rockets, such as ion and Hall-effect thrusters, use electricity (often from solar panels) to ionise and accelerate a propellant, typically xenon gas. These systems produce very low thrust but are incredibly efficient, allowing spacecraft to carry smaller amounts of fuel for long-duration missions. Electric propulsion is suitable for deep-space missions but not for launching from Earth's surface.
3. **Nuclear Thermal and Nuclear Electric Propulsion:** Nuclear propulsion systems are in experimental stages. Nuclear thermal rockets use nuclear reactions to heat a propellant, such as hydrogen, and expel it at high speeds to generate thrust. Nuclear electric propulsion uses nuclear power to generate electricity, which then powers an electric thruster. These systems have the potential for high efficiency and are ideal for long-duration missions beyond Earth's orbit.

Activity 3.2

Operation of Various Types of Gas Turbine Engines

1. In small groups, watch animation videos of how various types of gas turbine engines operate. While watching the video, note the following:
   - **a.** Identify notable parts of the gas turbine engines
   - **b.** Outline the various functions of these parts

   Discuss your answers with your peers in a class discussion.

   Video 1

   Video 2
2. In small groups, watch videos on how simple water rockets are made. While watching the video, make a note of the following:
   - **a.** Identify the notable parts of the rocket
   - **b.** Outline the various functions of these parts

   Discuss your answers with your peers in a class discussion.

   Water rocket 1

   Water rocket 2

3. In groups, source locally available materials to build and launch your own water rocket. Some basic materials required are plastic bottles, water, cardboard for fins and a bicycle pump. Document your observations for a discussion with your class.

Notes and Guidelines

a. Be careful when using sharp and pointy tools.
b. Keep your nose away from super glue if you have to use it. Direct inhalation may cause drowsiness.
c. Water rockets can produce powerful launches. Ensure everyone, except the one launching, stays 30 metres away from the launch spot. Guide rails may be used to guide the rocket up during the launch.

4. Your teacher will organise a visit to an aircraft maintenance facility to learn from the maintenance technicians through a class presentation about how gas turbine engines operate. Don't forget to document your observations! (If it is not possible to organise a visit to an aircraft maintenance facility, you could watch these videos on the subject instead:

Aircraft maintenance 1

Aircraft maintenance 2

Aircraft Maintenance 3

5. Organise yourselves into a small group of no more than five. Discuss the reason(s) for the dominance of rocket engines in spacecraft propulsion systems. Follow these headings to structure your discussion:

a. Fundamental Principles of Rocket Propulsion
b. High Efficiency in Vacuum Environments
c. Fuel and Energy Considerations
d. Manoeuvrability and Control in Space
e. Historical Development and Engineering Advancements
f. Limitations of Alternative Propulsion Systems
g. Reliability and Proven Success of Rocket Engines
h. Economics and Infrastructure for Rocket Propulsion
i. Future Prospects and Innovations in Rocket Engine Technology
j. Environmental and Sustainability Factors in Rocket Propulsion

Create a PowerPoint presentation to present your learning.

CALCULATING THE THRUST OF JET ENGINES

The primary requirement of any propulsion system is to be capable of providing enough thrust to propel the aircraft throughout its entire flight and during all manoeuvres. Aircraft designers therefore need to be able to quantify the thrust that a jet engine produces. The law of conservation of matter and momentum and Newton's third law of motion are used in finding a theoretical solution to finding the thrust of a jet engine.

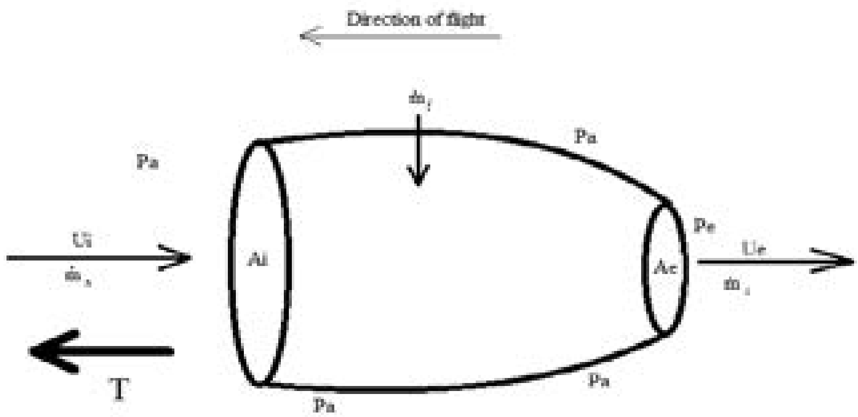


Figure 3.18: A jet engine

P_a is the pressure of the atmosphere

P_e is the pressure at the exhaust

A_i is the area of the inlet

A_e is the area of the exhaust

ρ is the air density

$\dot{\mathbf{m}}_{\mathbf{a}}$ is the mass flow rate of air entering into the engine

$\dot{\mathbf{m}}_{\mathbf{e}}$ is the mass flow rate of gases out of the exhaust

$\dot{\mathbf{m}}_{\mathbf{f}}$ is the mass flow rate of fuel into the combustion chamber

U_i is the inflow velocity

U_e is the exhaust velocity

The law of conservation of matter states that "matter cannot be created nor destroyed (except in a nuclear reaction"). By this principle, we can say that the total mass entering the engine should be equal to the total mass exiting the engine at any point in time. And since air and fuel are the only substances going into the engine and the exhaust gas is the only substance coming out of the engine, we can express this deduction mathematically as:

$$\dot{\mathbf{m}}_{\mathbf{e}} = \dot{\mathbf{m}}_{\mathbf{f}} + \dot{\mathbf{m}}_{\mathbf{a}}$$

This means that the mass of air and fuel going into the engine at any point in time should be equal to the mass of exhaust gases coming out of the engine at any point in time.

When air enters the engine its momentum forces the engine backwards, just like the wind will exert a force on a flat surface like a billboard. This force acts opposite to the direction of the thrust force and is called ram drag. It is quantified by the product of the mass flow rate and velocity of the incoming air. We can express it as:

$$D_{ram} = -\dot{\boldsymbol{m}}_{\mathbf{a}}\boldsymbol{u}_{\mathrm{i}}$$

It is given a negative sign because it acts against the direction of thrust.

Inside the engine, fuel is added to the air and burned. The air-fuel mixture exits the engine at high velocity through the exhaust nozzle. This creates a reaction force on the jet engine. This reaction force is the main contributor to the thrust produced by the jet engine and is called the absolute thrust. It is a product of the exhaust velocity and the sum of the mass flow rate of exhaust gases. Mathematically expressed as:

$$T_{abs} = \dot{\boldsymbol{m}}_{\mathbf{e}}\boldsymbol{U}_{\mathrm{e}}$$

The vector sum of the absolute thrust and the ram drag, when using the desired direction of T as the positive sign convention, is

$$T = T_{abs} - D_{ram}$$

$$T = \dot{\boldsymbol{m}}_{\mathbf{e}}\boldsymbol{U}_{\mathrm{e}} - \dot{\boldsymbol{m}}_{\mathbf{a}}\boldsymbol{u}_{\mathrm{i}}$$

The difference in exhaust pressure and ambient pressure contributes some amount to the thrust. This is called the pressure thrust. Taking the pressure thrust into account, the thrust equation becomes:

$$T = \dot{\boldsymbol{m}}_{\mathbf{e}}\boldsymbol{U}_{\mathrm{e}} - \dot{\boldsymbol{m}}_{\mathbf{a}}\boldsymbol{U}_{\mathrm{i}} + (P_{\mathrm{e}} - P_{\mathrm{a}})A_{\mathrm{e}}$$

Example 3.1

A jet engine has a circular inlet diameter of 1.2m and exhaust diameter of 0.45m. The mass flow rate of the ram air is 50kg/s. Fuel is being injected into the combustion chamber at 6kg/s. The ambient pressure is 101.3kPa and the pressure at the exhaust is 115.0kPa. If the air intake is 150m/s and the exhaust velocity is 600m/s,

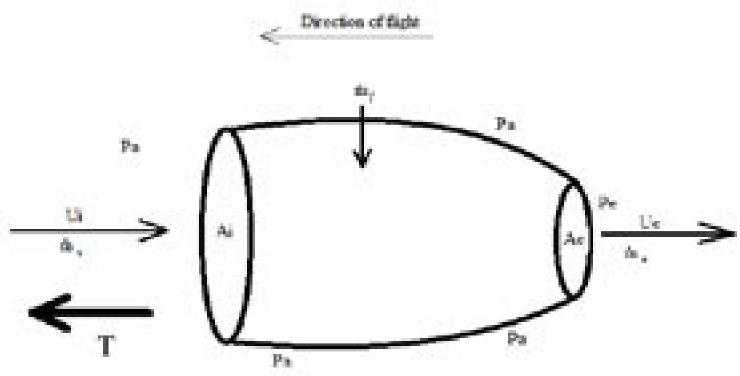


Figure 3.19: Jet engine analysis

a. Calculate the exhaust mass flow rate.

b. Calculate the ram drag.

c. Calculate the thrust force.

Solution

a. Using the law of conservation of matter, we can say that the mass entering the engine must be equal to the mass exiting the engine at any point in time. This means that the mass flow rate of the exhaust velocity is equal to the sum of the mass flow rate of the intake air and the mass flow rate of the injected fuel.

Where $\dot{m}_a$ is the mass flow rate of air, $\dot{m}_e$ is the mass flow rate of the exhaust gases and $\dot{m}_f$ is the mass flow rate of the fuel.

b. The ram drag is caused by the incoming air ramming into the engine. It is the product of the incoming air's mass flow rate and its velocity.

c. Using the thrust formula;

where;

$\dot{m}_e = 56\text{kg/s}$

$\dot{m}_a = 50\text{kg/s}$

$U_i = 150$ m/s

$U_e = 600$ m/s

$P_a = 101.3\text{kPa}$

$P_e = 115.0\text{kPa}$

The cross-sectional area of the exhaust is not explicitly stated in the question; however, it can be determined using the diameter of the exhaust which is mentioned in the question.

$$A_e = \pi r^2 = \pi \frac{d^2}{2^2} = \frac{d^2}{4}$$

$$A_e = \pi \frac{0.45^2}{4}$$

Substituting into the thrust equation;

$$T = (56)(600) - (50)(150) + (115000 - 101300)(0.159)$$

$$T = 33600 - 7500 + (13500)(0.159)$$

$$T = 26100 + 2146.5$$

$$T = 28246.5\ N$$

Activity 3.3

Solve Real-life Problems on Absolute Thrust of an Engine

1. Solve the following:
   - **a.** An aircraft jet engine expels gases at an exhaust velocity of 600 m/s. If the mass flow rate of the exhaust gases is 50 kg/s, calculate the absolute thrust of the engine.
   - **b.** A jet engine has an exhaust gas velocity of 700 m/s and air mass flow of 60 kg/s. The nozzle exit area is 0.5 m^2, with an exhaust pressure of 200 kPa and an ambient pressure of 100 kPa. Assuming the mass flow rate of fuel is 3kg/s, calculate the total thrust.
   - **c.** Suppose a jet engine is designed to operate with a variable mass flow rate $\dot{m}_a$ to adapt to different thrust requirements. If the exhaust velocity remains constant at 700 m/s, calculate the required mass flow rate to produce 10,000 N, 20,000 N, and 30,000 N of thrust, respectively.
2. In small groups, discuss the terms in the thrust equation and explain how they were derived.
   - **a.** absolute thrust
   - **b.** the ram drag
   - **c.** pressure difference

CALCULATING THE THRUST OF ROCKET ENGINES

Rocket engines are used predominantly in space propulsion systems, particularly because they are not air-breathing engines. They carry their fuel and oxidiser and hence can operate in a vacuum. This ability greatly simplifies the thrust equation of rockets because, unlike jet engines, they have no ram drag component and hence all the thrust is contributed by the reaction from the exhaust gases and the difference between exhaust pressure and ambient pressure.

The absolute thrust is

$$T = \dot{\boldsymbol{m}}_{\mathbf{e}} \boldsymbol{v}_{\mathbf{e}}$$

where:

T is the thrust force in Newtons (N),

$\dot{\mathbf{m}}_{\mathbf{e}}$ is the mass flow rate of the exhaust gases in kg/s,

$\mathbf{v}_{\mathbf{e}}$ is the velocity of the exhaust gases in m/s.

This is the reaction force generated due to the exhaust gases coming out of the nozzle.

Like the jet engine, the difference between the ambient pressure and the exhaust pressure contribute to the net thrust that act on a rocket. The pressure at the exhaust exerts an upward force (in the direction of the thrust) of magnitude:

$$F_{upward} = P_{\mathrm{e}} A_{\mathrm{e}}$$

The ambient pressure is distributed all around the rocket. Most of the forces created by the ambient pressure acting around the rocket cancel out except those acting directly over the area of the exhaust nozzle. This creates a downward force of magnitude:

$$F_{upward} = -P_{\mathrm{a}} A_{\mathrm{e}}$$

The negative sign signifies that the force acts in a direction opposite to the selected positive sign convention, which is upwards.

P_e is the pressure of the exhaust gases in Pa,

P_a is the ambient pressure in Pa,

A_e is the area of the exhaust nozzle in m^2

The net pressure thrust is:

$$T_{pressure} = F_{upward} + F_{downward}$$

$$T_{pressure} = P_{\mathrm{e}} A_{\mathrm{e}} - P_{\mathrm{a}} A_{\mathrm{e}}$$

$$T_{pressure} = (P_{\mathrm{e}} - P_{\mathrm{a}}) A_{\mathrm{e}}$$

Therefore, if the thrust contributed by the pressure differences and the thrust contributed by the expulsion of exhaust gases at high speeds, we get the general thrust equation.

$$T = \dot{\boldsymbol{m}}_{\mathbf{e}} \boldsymbol{v}_{\mathbf{e}} + (P_{\mathrm{e}} - P_{\mathrm{a}})A_{\mathrm{e}}$$

Example 3.2

A rocket engine expels gases at an exhaust velocity of 3,000 m/s with a mass flow rate of 20 kg/s. Calculate the thrust produced by the rocket, assuming the pressure thrust is negligible.

Solution:

We call on the thrust equation,

$$T = \dot{\boldsymbol{m}}_{\mathbf{e}} \boldsymbol{v}_{\mathbf{e}} + (P_{\mathrm{e}} - P_{\mathrm{a}})A_{\mathrm{e}}$$

However, the question indicates the pressure thrust is negligible, hence, the thrust equation reduces to

$$T = \dot{\boldsymbol{m}}_{\mathbf{e}} \boldsymbol{v}_{\mathbf{e}}$$

$$T = 3000 \times 20$$

$$T = 60{,}000\ N$$

Example 3.3

A rocket engine has an exhaust velocity of 2,500 m/s and a mass flow rate of 15 kg/s. The nozzle exit area is 0.3 m^2, with an exhaust pressure of 250 kPa and an ambient pressure of 150 kPa. Calculate the total thrust produced.

Solution:

The thrust equation is

$$T = \dot{\boldsymbol{m}}_{\mathbf{e}} \boldsymbol{v}_{\mathbf{e}} + (P_{\mathrm{e}} - P_{\mathrm{a}})A_{\mathrm{e}}$$

This time we need to factor in the pressure difference.

$$\mathrm{T} = (15 \times 2{,}500) + (250{,}000 - 150{,}000) \times 0.3$$

$$\mathrm{T} = 37{,}500 + 30{,}000$$

$$\mathrm{T} = 67{,}500$$

Activity 3.4

Solve Real-life Problems

1. Write down the jet and rocket equations in full. Compare the two equations and note their similarities and differences. What features of these engines dictates these similarities and differences?

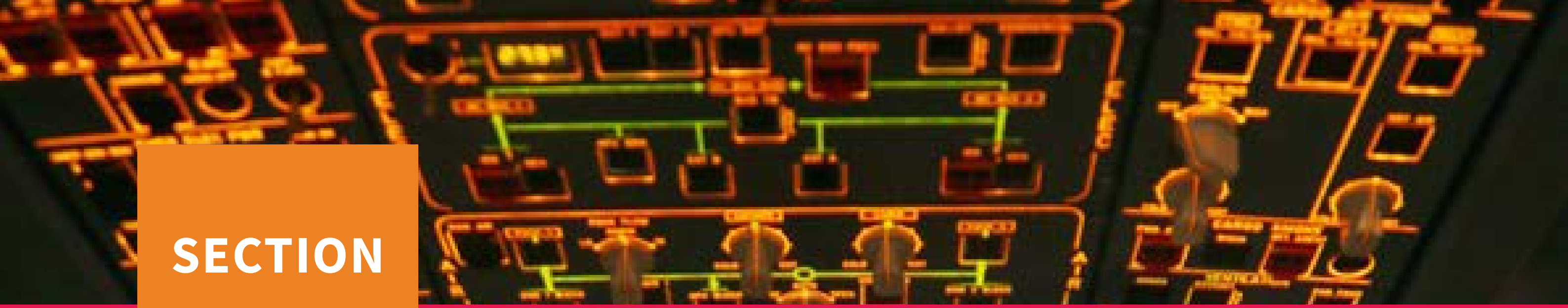
2. Return to the water rocket that you built in the earlier activity. Vary the amount of water and the pressure pumped. Observe how high the bottle rises and relate that to the rate of change in momentum at the nozzle of a rocket.
3. Solve the following questions:
   a. A rocket engine produces 50,000 N of thrust with an exhaust velocity of 2,000 m/s. Determine the mass flow rate of the exhaust gases. Ignore pressure differences (as being negligible).
   b. A rocket engine needs to generate 30,000 N of thrust. If the mass flow rate of the exhaust gases is 10 kg/s, what exhaust velocity is required to achieve this thrust if the exhaust pressure is only 10 KPa greater than the ambient pressure?

EXTENDED READING

- Aircraft Propulsion and Gas Turbine Engines by Ahmed El Sayed
- How does a #hydrogen fuel cell work? | what is #hydrogen fuel cell | #hydrogencell explain
- Rocket Propulsion Elements by George Sutton and Oscar Biblarz
- What Is a Rocket? (Grades 5-8) - NASA

Review Questions

1. In brief, describe a reaction engine. Give two examples of reaction engines used in modern-day aviation/aerospace travel.
2. Aside aircraft propulsion, name two other activities that make use of the law of action and reaction.
3. A turbojet engine on an aircraft produces an exhaust gas velocity of 700 m/s with a mass flow rate of 50 kg/s. At sea level, where the ambient pressure is 101.3 kPa, the nozzle exit pressure is 150 kPa, and the nozzle exit area is 0.4 m^2. The mass flow rate of fuel is 2.8kg/s. Calculate the thrust at sea level if the intake velocity is 250m/s.
4. A rocket engine at sea level has an exhaust velocity of 2,800 m/s and a mass flow rate of 25 kg/s. The nozzle exit area is 0.8 m^2, and the exhaust pressure is 300 kPa, with an ambient pressure of 101.3 kPa. Calculate the thrust at sea level.



SECTION

4

AIRCRAFT INSTRUMENTS

AVIONICS

Aircraft Instrumentation

INTRODUCTION

This section contains information about aircraft instruments and flight data storage equipment. You will learn about the principles of operation of several instruments and the information they provide to pilots. You will also learn about the aircraft's "black box" which stores flight data and audio that helps accident investigators piece together the events that led to an air crash.

Key Ideas

- A measurement instrument provides us with a representation of the value of a physical variable of interest
- Flight data recorders provide air crash investigators with information that helps them determine the cause of the accident.
- The output of an instrument may be displayed to a human operator or recorded for future analysis

FLIGHT INSTRUMENTS

Measurement systems or instruments provide information about the value of a parameter of interest. The parameter of interest is called the measurand whiles the instrument output is often just referred to as the measurement.

Aircraft instruments provide the pilot with information about the state of the aircraft and its subsystems. We will learn about the basic flight instruments, which measure parameters directly related to the flight of the aircraft and that help the pilot to navigate to their destination. Six of these stand out; they are, the airspeed indicator, attitude indicator, horizontal situation/heading indicator, altimeter, turn coordinator and vertical speed indicator. Traditionally, these instruments may be classified as *barometric* instruments or *gyroscopic* instruments.

Barometric Instruments

The barometric instruments work by taking a measurement of air pressure. This may be the static pressure – the pressure of the air due to the position of the aircraft in the atmosphere, or pitot/total pressure – the summation of static pressure and that pressure due to the relative motion between the aircraft and the atmosphere, the dynamic pressure. Aircraft may have a dedicated static port and pitot probe or a pitot-static probe that measures both static and pitot pressure. **Figure 4.1** shows the pitot-static system of an aircraft. Of the six basic flight instruments, the airspeed indicator, vertical speed indicator and altimeter are barometric instruments. Let us take them one by one.

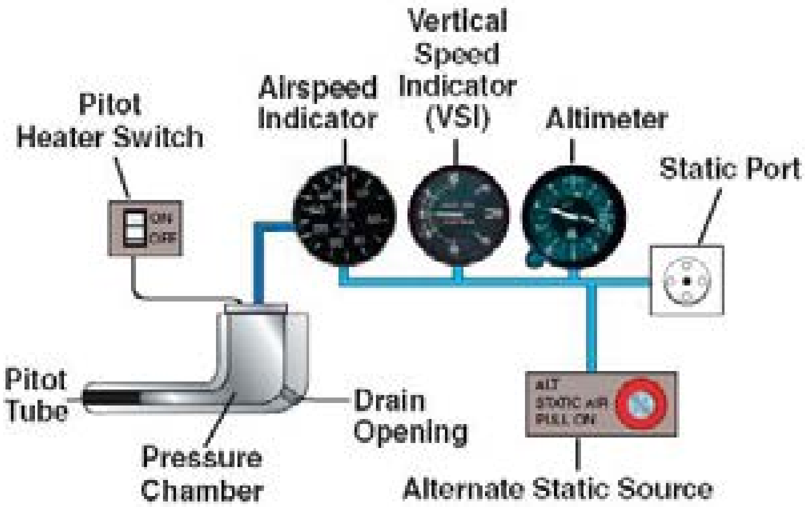


Figure 4.1: Aircraft pitot-static system (Source: Wikipedia)

Airspeed Indicator

Just like its name, this instrument indicates the speed of the aircraft through the air. A measurement is registered even if the aircraft is stationary. What is required is that there is relative motion between the aircraft and the surrounding air. The airspeed indicator utilises both static and pitot pressure. A fixed-wing aircraft remains afloat by moving through the air. The airspeed indicator is therefore a means for the pilot to ascertain the performance of the aircraft. If it goes too slow, it might stall, and if it goes too fast, faster than the manufacturer's never-exceed speed, it may suffer structural damage. The scale of the airspeed indicator may be colour coded. The green region indicates the normal operating range, the white region, the speed range for operating the flaps, the yellow region, a caution region and the red, never-exceed speed limit. Airspeed is usually provided in knots (nautical miles per hour); there are 1852 metres in a nautical mile. Figure 4.2 shows the face of a typical airspeed indicator.

Figure 4.2: Airspeed indicator (Source: Flight Nerd Air Force)

Activity 4.1

Converting between Airspeed Units

If an airspeed indicator registers a speed of 45 knots, what is the speed of the aircraft in km/h?

Vertical Speed Indicator

The vertical speed indicator tells the pilot how fast the aircraft is rising or falling. It makes use only of static pressure. It has two input ports; one receives unrestricted static pressure, while the other receives static pressure through a calibrated/metered leak. An increase or decrease in altitude establishes a gradient between the two sources, indicating the rate of climb or descent of the aircraft. The scale of the vertical speed indicator may be calibrated in hundreds of feet per minute. **Figure 4.3** shows the face of a vertical speed indicator.

Figure 4.3: A vertical speed indicator (Source: Wikipedia)

Altimeter

The altimeter measures the altitude of the aircraft. You remember studying about the International Standard Atmosphere in an earlier lesson, well, the altimeter operates using this model. It registers how high the aircraft is relative to a datum using a measurement of the static pressure. Pilots usually receive updates about the local pressure on the surface from a flight information service. They input this into their altimeter so that it reads the height above that station. This way, all aircraft flying within a particular area use the same reference and are effectively separated from each other. The readings from the altimeter may be in feet. 1-foot equals 0.3048 meters. **Figure 4.4** shows an altimeter.

Figure 4.4: Altimeter (Source: Flying Magazine)

For applications where it is desired to determine the height of the aircraft above terrain, especially for flight close to the earth, a radio altimeter may be used. It measures the height above the ground by sending and receiving an echo from a radio wave transmitted from the aircraft to the ground.

Activity 4.2

Altitude from a Radio Altimeter

The radio altimeter of an aircraft sends out a 450 MHz signal towards the ground and receives an echo after 2 microseconds. How high is the aircraft above the ground? [Take speed of light to be 3×10^8 m/s]

Gyroscopic Instruments

Gyroscopic instruments work by taking a measurement of an aircraft's rotation. Traditional mechanical gyroscopes exploit their precession and rigidity in space to provide these measurements. More recently, microelectronic devices are replacing the older systems. The attitude indicator, turn coordinator and horizontal situation/

heading indicator are all gyroscopic instruments. Let us consider them one after the other.

Attitude Indicator

The attitude indicator provides the pilot with a pictorial representation of the orientation of the aircraft relative to the horizon. Blue and brown horizontal sections meet at the centre of the instrument which represents the horizon. An aircraft symbol registers against this background to provide the orientation. The pilot can tell his/her pitch and roll attitude using this instrument. **Figure 4.5** is an illustration of aircraft attitude, while **Figure 4.6** shows a typical attitude indicator.

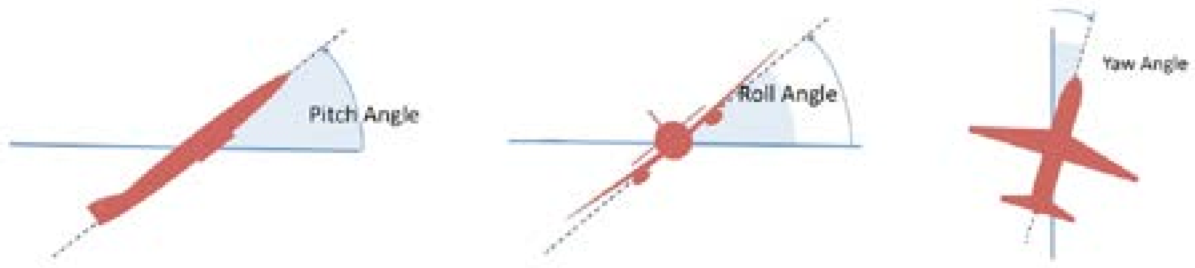


Figure 4.5: Aircraft roll, pitch and yaw attitude

Figure 4.6: Aircraft attitude indicator (Source: MidContinent Instruments and Avionics)

Horizontal Situation/Heading Indicator

This instrument shows the pilot his bearing relative to magnetic north. It is often implemented as a gyro-stabilised compass. It helps the pilot to navigate from one waypoint to another. Without this instrument, a pilot may go off-course, ending up in a destination several kilometres away from his intended destination. **Figure 4.7** shows a heading indicator.

Figure 4.7: Heading indicator (Source: Pilot Workshop)

Turn Coordinator

The turn coordinator provides information about the rate and quality of a turn. If an aircraft turns at a rate commensurate with the angle of bank, it is said that the turn is coordinated. If the rate of turn is higher than required for the bank angle, the aircraft is said to skid. In the opposite situation, the aircraft is said to be slipping. The quality of turn is indicated by a ball in a glass tube. The ball is centred in a coordinated turn. Pilots are taught to “step on the ball” to correct the turn. **Figure 4.8** shows an aircraft’s turn coordinator.

Figure 4.8: Turn coordinator (Source: Pilot Institute)

Activity 4.3

Identifying Critical Environmental Variables

In a small group, brainstorm and identify critical environmental variables (including aircraft data) that pilots need to ensure safe flight. Discuss your findings with the whole class in a discussion.

Activity 4.4

Identifying Aircraft Instruments

1. Your teacher will show you pictures of the basic flight instruments. Do your best to try to name them.
2. Watch this video on the basic aircraft instruments: Click here
3. Write a report on the basic instruments you observed in the video and the quantities they measure.

Activity 4.5

Matching Instruments with their Quantities

Match the instruments on the left with the quantities they measure on the right.

Altimeter		Aircraft pitch and roll
Airspeed indicator		Altitude
Attitude indicator		Airspeed
Turn coordinator		Direction of travel
Horizontal situation indicator		Rate of climb or descent
Vertical speed indicator		Rate and quality of turn

Primary Flight Display

With the advancement of electronics and its incorporation into the design of avionics systems, the cockpit display environment has been transformed from a panel with several individual dial-type instrument displays to a "glass cockpit" with an integrated instrument display system.

The primary flight display (PFD) incorporates all the previously mentioned flight instruments in one place using advanced computer graphics. This reduces the amount of time pilots would have to scan the instrument panel to read instruments. Also, the layout of instruments on the PFD largely follows the traditional layout. This makes it easy for pilots to transition from a traditional cockpit to newer or upgraded aircraft. Figure 4.9 shows a typical PFD screen.

Figure 4.9: Primary flight display (Source: Pilot's Handbook of Aeronautical Knowledge)

ENGINE INDICATING INSTRUMENTS

The engine or powerplant of an aircraft is what provides the power for it to move. It is important, therefore, for the pilot to have a current picture of its operating condition at all times. Engine indicating instruments make this possible; they provide the pilot with information related to the performance and health of the engine(s). Some instruments may be found on piston engines only or turbine engines only, whereas others may be common to both. Let us take them one at a time.

Tachometer

An aircraft's engine generates thrust by driving a propeller or ejecting a stream of high-velocity gases outward. It is desirable to know the speed of rotation of the propeller or turbine, or compressor stage (in a jet engine), and this is where a tachometer comes in handy. It gives a reading of the engine speed, usually in revolutions per minute (RPM). Aircraft manufacturers specify acceptable values of engine speed for different operating conditions. With the help of this instrument, the pilot can determine if the engine is operating normally, and whether the flight can proceed. **Figure 4.10** shows the face of a typical aircraft tachometer. The hours counter at the bottom shows how long the engine has been running.

Figure 4.10: Aircraft tachometer (Source: Aircraft Spruce and Specialty Company)

Manifold pressure gauge

This instrument finds use in piston-engine aircraft. It measures the absolute pressure of the fuel-air mixture in the engine's intake manifold. This is an indication of the power developed by the engine. It may also serve as a means of determining altitude in an emergency. Measurements are usually provided in inches of mercury (inHg). 1 inHg is equivalent to 3386.389 pascals. **Figure 4.11** shows a typical aircraft manifold pressure gauge.

Figure 4.11: Manifold pressure gauge

Activity 4.6

Manifold Pressure Calculation

An aircraft's manifold pressure gauge records a measurement of 15 inHg. Knowing that the density of mercury is 13,600 kg/m^3, find the equivalent value of this reading in kilopascals. [Take acceleration due to gravity, g = 9.81 m/s^2]

Oil Temperature Gauge

Special oil is used to lubricate aircraft engines. The temperature of the engine oil reflects how well the engine is being cooled. Excessively high temperatures may imply cooling system failures, insufficient oil or excessive thrust settings and can lead to engine failure. The oil temperature gauge allows the pilot, thus, to monitor the operating temperature of the engine to ensure that it operates optimally in all conditions. Readings are normally indicated in **Figure 4.12** shows a typical aircraft oil temperature gauge.

Figure 4.12: Oil temperature gauge (Source: BAS Part Sales LLC)

Oil Pressure Gauge

Another important parameter of engine oil that needs to be measured is its pressure. Oil pressure is an indication of whether the engine is receiving adequate oil for lubrication and cooling of its internal components. A low-pressure reading may indicate oil leakage, pump failure or excessive engine wear. Engine damage may result if oil pressure drops below a critical value. Oil pressure readings are usually provided in psi (pounds per square inch). 1 psi is equal to 6894.76 pascals. **Figure 4.13** is a picture of an aircraft oil pressure gauge. Often, the oil pressure gauge shares the same display with the oil temperature gauge. An example of this is shown in **Figure 4.14**.

Figure 4.13: Oil pressure gauge (Source: Aircraft Spruce and Specialty Company)

Figure 4.14: Shared oil temperature and pressure display (Source: Aviation Instrument Service)

Exhaust gas temperature gauge

The exhaust gas temperature (EGT) gauge provides a measure of the temperature of the hot gases that exit the engine. This gives an indication of the engine's health, performance and efficiency. It is also an indication of the balance of the fuel and air mixture that enters the combustion chamber. A low EGT can result from a lean mixture (too little fuel) indicating improved fuel efficiency, whiles a high EGT usually results from a rich mixture (high fuel to air ratio) and may indicate high fuel consumption. The EGT of a jet engine typically fluctuates between 600 ^{0}C and 1000 ^{0}C. For a piston engine, it is usually in the range 700 ^{0}C – 800 ^{0}C. **Figure 4.15** shows a typical aircraft EGT gauge.

Figure 4.15: Exhaust gas temperature gauge

Fuel Quantity Indicator/ Fuel Gauge

This instrument measures the amount of fuel in the aircraft's storage tanks. This information helps the pilot plan the flight duration, routes and fuel consumption. It also assists the crew to avoid running out of fuel or exceeding the maximum take-off or landing weight. Some aircraft use float-type gauges that provide a measurement based on the position of a bob that floats on the fuel. Other approaches of measuring the fuel level include the exploitation of varying capacitance due to the height of fuel or pressure at the bottom of the fuel tanks. This instrument usually provides a reading of fuel weight (usually in pounds) or volume (usually in gallons or litres). Sometimes, the gauge may display the fraction/percentage of fuel remaining in the tank. **Figure 4.16** shows examples of these. [1 gallon is approximately 0.00379 m^3; 1 pound (lb) is approximately 0.4536 kg.]

Figure 4.16: Fuel gauges (Source: Aircraft Spruce)

Fuel flow indicator

The fuel flow indicator provides a measurement of the rate of fuel consumption by the engine. It is usually provided in gallons - or litres per hour. It allows for better fuel management and planning during flight and is especially critical during long flights or cases where fuel consumption changes due to fluctuations in engine power settings or altitude. **Figure 4.17** shows a typical aircraft fuel flow meter.

Figure 4.18: Aircraft fuel flow meter (Source: Aircraft Spruce and Specialty Company)

Activity 4.7

Fuel Flow Calculations

A Cessna 172 has a 52-gallon (236 lites) capacity fuel tank installed. During a flight that lasts approximately 45 minutes, the pilot records an average fuel consumption of 12 gallons per hour (54.5 litres/hr). What fraction of fuel remains after the flight?

Engine Pressure Ratio Indicator

This instrument finds use on turbojet engines. It provides a measurement of the ratio of the pressure of intake air to exhaust gas, which may be used to estimate the thrust produced by the engine. **Figure 4.19** is an example of an aircraft engine pressure ratio indicator.

Figure 4.19: Engine pressure ratio indicator (Source: Bendix)

Turbine Inlet Temperature Gauge

This instrument measures the temperature of gases that enter the turbine stage of a jet engine. This value, together with the engine speed, can be used to estimate the thrust produced by the engine. It also gives an indication of the thermal stress the turbine blades undergo and is critical to preventing their failure. **Figure 4.20** shows a turbine inlet temperature gauge.

Figure 4.20: Turbine inlet temperature gauge (Source: Innovative Solutions and Support)

Vibration monitoring and indicating systems

It is nearly impossible to eliminate vibration in an aircraft engine, even with turbine engines, which have no reciprocating parts. High vibration levels can lead to performance degradation and ultimately, mechanical failure. There is therefore a need for a means of monitoring engine vibration and indicating when its maximum amplitude exceeds a preset level. A pickup system measures this parameter and provides an indication, usually in units of mils (thousandths of an inch), to the pilot. An indicator light also turns on when the preset vibration level is exceeded.

Activity 4.8

Automotive Versus Aircraft Instrumentation

1. Discuss with a friend which instruments you believe are common to both aircraft and automobiles.
2. Share your views with the entire class.

Activity 4.9

Operation of an Airspeed Indicator

1. Research using the internet or by visiting the local library, how the airspeed indicator of an aircraft works
2. Write a short report on your findings.

Activity 4.10

How Engine Indicating Instruments Work

1. Your teacher will visit an aircraft maintenance facility. During your visit, observe some engine indicating instruments and how they work. Engage in a class discussion and discuss your observations with your peers.
2. Alternatively, in the absence of a nearby aircraft maintenance facility, videos on engine instruments can be used to supplement class discussions.

   Aeroplane instruments 1

   Aeroplane instrument 2

   Aeroplane engine instruments

Activity 4.11

Troubleshooting Instrument Failure

Which of the pitot static instruments do you think would be affected if an aircraft's pitot tube is blocked? (See videos above if help is required.)

FLIGHT DATA STORAGE EQUIPMENT

Flight is arguably the safest mode of transport today. One reason for this is that strict regulations are applied to the development and operation of aircraft and their systems. Another reason is that accidents/incidents that occur are investigated, and the recommendations from this are carried out throughout the industry.

One piece of equipment that supports accident/incident investigations is the cockpit voice recorder (CVR). It gathers and stores recorded audio to help investigators determine what happened during the accident, what caused the accident and what could be done to prevent it from happening again in the future. **Figure 4.21** shows a picture of a CVR.

Figure 4.21: Cockpit voice recorder

The CVR unit comprises the electronics that control the system and a crash-protected enclosure that protects the recorded data. There is also, usually, an underwater locator beacon attached to it that emits a signal to help rescue services locate and recover it even if it gets submerged in water.

The CVR records other inputs as well, although its primary function is to record audio. A typical CVR can record

a. Four channels of audio (Pilot, co-pilot, third crew member or passenger address system and a cockpit area microphone)

b. Coordinated Universal Time (UTC), often called Greenwich Mean Time (GMT)

c. Rotor speed in rotorcraft applications

d. Datalink communication messages

The CVR has an independent backup power supply that provides between 9 and 11 minutes of power. There are also additional inputs to prevent the CVR from being erased in flight, to stop recording within 10 minutes after impact and to prevent recording if the unit is not installed on an aircraft.

Previously, magnetic tapes were used to record the information. Later regulations required the use of solid-state recording technology. Modern CVRs store the last 2 hours of recorded data; they are periodically inspected to ensure that they are fully functional.

Flight data recorders (FDRs) are like CVRs and regulations for their development and operation are often included with those for CVRs. They record flight data, such as, time, altitude, airspeed, heading, flap position, attitude and autopilot mode. The data stored can be used to ascertain whether a crash was caused by mechanical failures, environmental factors or human error. It is also used by manufacturers to improve upon future designs and related systems.

Where both a CVR and FDR are required to be installed on an aircraft, recent regulations require that they are in a separate container. Flight recorders are painted bright orange so that they can be easily spotted among the wreckage. They are designed to withstand high levels of shock, temperature and pressure. They are colloquially referred to as "black boxes."

Activity 4.12

Design Features of Flight Data Recorders

1. Organise yourselves into groups of no more than five. In your groups, discuss the design features of flight data recorders.
2. Write down bullet points about the importance of flight data recorders.
3. Engage in a class discussion where each group provides their input.

Activity 4.13

Accident Case Study

Read the story of an aircraft accident that follows, and provide answers to the following questions.

1. Which part of the pitot static system could have been affected by the icy air conditions?
2. Why do you think the icy air conditions prevailed over the aircraft?
3. Which component of the aircraft provided the accident investigators with recordings of flight data and the pilots' utterances?

Air France Flight 447 was scheduled to fly passengers from Rio de Janeiro, Brazil, to Paris, France. The aircraft departed from Rio de Janeiro–Galeão International Airport on 31 May 2009 at 19:29 Brazilian Standard Time (22:29 UTC)with a scheduled arrival at Paris-Charles de Gaulle Airport at 11:03 Central European Summer Time (09:03 UTC) the following day.

Three and a half hours into the flight over the Inter-Tropical Convergent Zone, ice started to build up in the airspeed sensors. The airspeed indications in the cockpit showed inconsistent readings. This caused the autopilot to disengage and remove the protections inherent in the system. The surprised pilots had to fly the aircraft manually. They mistakenly over-controlled the aircraft when it started to roll from *side to side. This caused the aircraft to roll left and descend sharply. To level off, the pilots again overcorrected and pulled back on the controls until the aircraft stalled.*

The aircraft then entered a free-fall towards the ground. The pilots misinterpreted this as an overspeed. They reduced engine thrust and applied the speed brakes, the exact opposite of what they needed to do to recover from the stall. Further, the pilot and copilot made contradictory inputs on the controls.

By the time the crew realised the situation, the aircraft was too close to the surface to recover from the stall. The aircraft crashed into the sea and broke apart, killing all passengers and crew onboard. A total 228 people lost their lives that day. After two years of searching underwater, the flight data recorder and cockpit voice recorder were recovered. Aviation units used the transcripts to piece together the sequence of the incident.

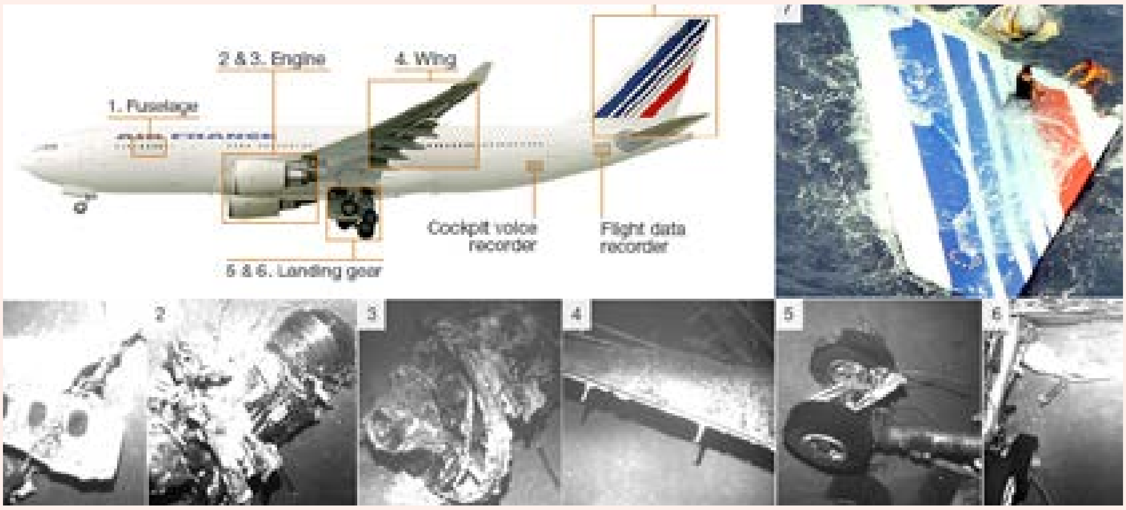


Figure 4.22: Recovered debris from Air France Flight 447
https://www.bbc.co.uk/news/world-europe-13145313

Activity 4.14

Importance of Flight Data Recorders in Aircraft Accident Cases

Watch this video about aircraft accident cases in which flight data recorders were used to detect possible causes of the accidents. As you watch the video, make notes on why you think flight data recorders are important. Present your findings to the class in a whole-class discussion.

Aircraft accident case- Click here

EXTENDED READING

- Flight instruments - click here
- Flight recorder - click here
- Primary flight display - click here

Review Questions

1. What bit of information does a pilot lose if his horizontal situation indicator fails?
   - **A.** Airspeed
   - **B.** Altitude
   - **C.** Attitude
   - **D.** Bearing
2. Which of the following flight instruments reads “0” when an aircraft is parked in still air?
   - **A.** Vertical speed indicator
   - **B.** Airspeed indicator
   - **C.** Altimeter
   - **D.** All the above
3. How long does a pilot need to climb if he needs to gain 500 metres in altitude with instructions from air traffic control to maintain a rate of climb of 100 feet per minute?

SECTION

5

LOCAL AND INTERNATIONAL CIVIL AVIATION BODIES

AVIATION INDUSTRY

Aviation Organisations

INTRODUCTION

In this section, we'll look at the organisations that play a major role in aviation. This includes a local body and several international organisations. We'll consider the functions they play in the industry and how these contribute to the overall safety of air travellers worldwide.

Key ideas

- Aviation is a global industry with players from all over the globe.
- National organisations develop regulations for aviation within their jurisdiction, referring to international standards and regulations developed by the International Civil Aviation Organisation.
- Safety is taken very seriously in the aviation industry.

CIVIL AVIATION ORGANISATIONS

Civil aircraft are used to provide air services to many people around the world. Several firms exist in this space, providing services ranging from cargo flights to charter flights. There are also the companies that manufacture aircraft and aircraft related systems. Seeing as air travel is the safest form of travel, and the desire to continue to make it so, there is the need to regulate the actions of these enterprises to ensure that the highest standards of safety are adhered to. Besides this, there is also the need to bring together these players to exchange ideas and push for favourable regulations. For these reasons, several organisations have been established, both locally and internationally. They include the Ghana Civil Aviation Authority, the International Civil Aviation Organisation, the International Air Transport Association, the Federal Aviation Administration of the United States and the European Union Aviation Safety Agency. Let us consider these agencies one after the other beginning with the local body.

Ghana Civil Aviation Authority

The Ghana Civil Aviation Authority (GCAA) is the agency responsible for regulation of air transportation in Ghana. It is also responsible for providing air navigation services over Ghana's airspace and a large part of the Atlantic Ocean in the Gulf of Guinea. **Figure 5.1** shows the logo of the GCAA.

Figure 5.1: GCAA logo (Source: GCAA)

GCAA was established on May 16, 1986, for this purpose, and to operate and manage all aerodromes in the country. In November of 2004, the act that established GCAA was amended; it mandated GCAA to cede its airport management function to the Ghana Airports Company Limited, enabling it to focus on regulating the air transport industry and providing air navigation services. A new regulation, promulgated in August 2024 re-established the GCAA as an autonomous body responsible for aviation safety and security in Ghana.

The GCAA performs a range of functions, including:

1. Ensuring compliance with international standards of civil aviation
2. Advising government on matters related to civil aviation
3. Giving effect to civil aviation treaties that Ghana enters
4. Regulating aviation security in Ghana
5. Regulating airports and airport service providers in the country
6. Regulating flight standards in the civil aviation industry including the licensing, certification and approval of aircraft, air operators, flight crew and licensed aviation personnel

Activity 5.1

Functions of GCAA

1. Join a school field trip to GCAA to interact with the staff of the organisation and learn from them what they do. (If a field trip is not possible, watch this video instead:
   Ghana Civil Aviation Authority)

2. In pairs, discuss any three roles played by the GCAA in Ghana. Share your insights with the class during a whole-class discussion.
3. Write a report on your observations of what the Ghana Civil Aviation Authority does, either based on your visit or the video.

International Civil Aviation Organisation

The International Civil Aviation Organisation (ICAO) is an agency of the United Nations. It is funded and directed by 193 national governments. It exists for the mutual benefit of all these countries. **Figure 5.2** shows the logo of ICAO.

Figure 5.2: ICAO logo

ICAO was established in 1944 and has since supported countries diplomatically and technically to realise a rapid and dependable network of global air mobility and has promoted sustainable growth and socio-economic prosperity "wherever aircraft fly."

The core function of ICAO is to maintain an administrative and expert bureaucracy supporting diplomatic interactions and cooperation in air transport. Besides these, it helps to realise safe, secure and sustainable air operations on a global basis, conducts educational outreach, auditing, training and capacity building activities worldwide.

Activity 5.2

Relationship between GCAA and ICAO

1. What relationship exists between the GCAA and ICAO?
2. Watch these videos to help understand the relationship between the GCAA and ICAO:

   GCAA & ICAO 1 - CLICK HERE

   GCAA & ICAO -CLICK HERE 2

   - ICAO is an international organisation, while GCAA is Ghana's aviation regulation body.
   - ICAO develops guidelines which are adopted and implemented by GCAA.

International Air Transport Association

The International Air Transport Association (IATA) is the trade association for airlines around the globe. It represents over 330 airlines in 124 countries, accounting for about 80% of global air traffic. IATA was founded in 1945 in Havana, Cuba. **Figure 5.3** shows its logo.

Figure 5.3: Logo of the International Air Transport Association (Source: IATA)

IATA has offices in 53 countries. Its head office is in Montreal, Canada, executive office in Geneva, Switzerland and government affairs offices in Brussels and Washington, D.C. Its mission is to represent, lead and serve the airline industry, and it aims to "shape the future growth of a safe, secure and sustainable air transport industry."

IATA organises a general meeting and air transport summit annually. It is attended by representatives from IATA member airlines, industry partners, international and regional associations, manufacturers and suppliers, and the government. Through this avenue, IATA formalises industry positions on industry and public policy issues and provides a focus on emerging industry issues.

IATA strives to promote safety in the aviation industry. It has been mandated to carry this out at the state level by several countries. It does this through its IATA Operational Safety Audit. Through its efforts, air travel continues to remain one of the safest means of travel. Environmentally-friendly initiatives are also being implemented to ensure that net carbon emissions are greatly reduced.

Federal Aviation Administration

The Federal Aviation Administration (FAA) is the U.S. government agency responsible for regulating civil aviation in the United States and surrounding international waters. **Figure 5.4** shows the seal of the FAA.

Figure 5.4: FAA seal (Source: FAA)

The FAA provides air navigation services within the U.S. national airspace system; certifies aircraft and personnel, including pilots, mechanics and airlines; plans and develops the airport system within the U.S.; sees to the protection of U.S. assets during the launch and re-entry of commercial space vehicles; and develops and carries out programs that help to control the negative environmental effects of civil aviation.

European Union Aviation Safety Agency

The European Union Aviation Safety Agency (EASA) is the agency of the European Commission responsible for civil aviation safety in the European Union. It was established in 2018 and performs regulatory and executive tasks in the field of civil aviation safety and environmental protection within the European Union (EU). **Figure 5.5** shows EASA's logo.

Figure 5.5: EASA logo (Source: EASA)

EASA is headquartered in Cologne, Germany and acts as a "single specialised expert body," assisting EU institutions to prepare rules that govern the safety and environmental sustainability of aviation and verify their implementation at the national level.

The major functions performed by EASA include:

1. Drafting aviation safety legislation and providing technical advice to the European Commission and to the Member States
2. Carrying out inspections, training and standardisation programmes to ensure uniform implementation of European aviation safety legislation in all Member States
3. Safety and environmental type-certification of aircraft, engines and parts

4. Approval of aircraft design organisations world-wide as and of production and maintenance organisations outside the EU
5. Authorisation of third country (non-EU) operators
6. Data collection, analysis and research to improve aviation safety
7. Coordination of the European Community programme Safety Assessment of Foreign Aircraft regarding the safety of foreign aircraft using Community airports

EXTENDED READING

- FAA - Federal Aviation Administration (FAA) | Definition, Functions, History, & Organization | Britannica
- GCAA - About GCAA – GHANA CIVIL AVIATION AUTHORITY
- ICAO - International Civil Aviation Organization (ICAO) | Britannica

Review Questions

1. Name one local and two international aviation organisations
2. How does the GCAA ensure safety in civil aviation in Ghana?
3. A Ghanaian aircraft company is selected to develop an aircraft for a European airline. Which of the aviation organisations will it have to deal with?

SECTION

6

UAV LAWS AND SAFETY PRACTICES

UNMANNED AERIAL VEHICLES (UAVS)

UAV Safety and Regulations

INTRODUCTION

Unmanned aerial vehicles are quickly becoming integrated into the operations of many industries. Although one could say that the drone industry is still in its infancy, the world has experienced the effects that drones can have on daily life. Agriculture, security surveillance, mapping, mineral exploration, firefighting, entertainment, delivery services and defence are some of the sectors that drones have transformed. Also, due to the massive popularisation of drones, many private individuals are purchasing and using drones. As much as drones are beneficial to our daily life, if not properly regulated, they can be used to create mischief and their improper or irresponsible use may also cause injury to people or damage to property. In view of this, the Ghana Civil Aviation Organisation has laid some laws to regulate the acquisition and operation of drones in Ghana's airspace. This section highlights the directives and legalities of drone operations. It discusses the roles of the GCAA in certifying individuals and organisations, and also responsibilities of drone operators to adhere to the directives of the GCAA. We will also look into some standard and recommended practices regarding the operation of drones and the role that simulators play in the UAV industry particularly with regard to enhancing safety in training new drone pilots.

Key ideas

- Flight simulation plays a big role in enhancing safety in the testing of new aircraft and training of pilots.
- It is required by law that all UAV operators be certificated by the GCAA.
- The directives of the GCAA are to ensure that UAV operations are safe for the crew, by-standers and property.

THE GHANA CIVIL AVIATION AUTHORITY UAV REGULATIONS

The Ghana Civil Aviation Authority is the body responsible for managing Ghana's airspace. Any artificial object that flies in Ghana's airspace must first seek permission from the GCAA. It has become very important to implement a robust framework to regulate drone operations in our airspace considering the fact that drones have become an integral part of our daily lives

The Ghana Civil Aviation Directive (GCAD) Part 28 outlines the rules and regulations that govern the operations of remotely-piloted aircraft systems in Ghana. The directives outlined in the Part 28 provide RPAS operators with the rules required to safely integrate RPAS operations into Ghana's airspace infrastructure without interfering with manned aircraft.

In the Ghana Civil Aviation Directives Part 28, there are some general regulations that apply to all unmanned aircraft in Ghana's airspace. These are:

1. The Part 28 Directive addresses the protection of persons and property from mid-air collisions (MACs), accidents and incidents involving RPAS. It is the aim of this directive to ensure that RPAS operators conduct their operations in a way that minimises dangers posed to the crew, bystanders, property and other aircraft.
2. No UAV operator is allowed to control two or more UAVs with one RPS unless authorised by the GCAA. RPAS operators are not allowed to control more than one drone from a single ground station without first receiving authorisation from the GCAA. This extends to drone swarms as well.
3. No individual or organisation is permitted to operate UAVs for commercial activities unless the individual or organisation has been granted an RPAS operator certificate (ROC) by the GCAA.
4. No organisation or individual is permitted to organise training sessions for any aspect of UAV operations unless they have been granted an RPAS training organisation certificate (RTOC) by the GCAA.
5. UAV operators are not permitted to fly in restricted, prohibited, danger areas and Special Use Areas (SUA) unless they seek prior authorisation from the GCAA and any other relevant government agencies. Take for example, airports, the Jubilee House, military facilities and bases and prisons. Find the list of GCAA-designated no-fly-zones in Ghana at AC 28-009 - RPAS NO Fly Zones.pdf.
6. All unmanned aircraft operations are restricted to an altitude of 120m (400ft) above ground level. No UAV is permitted to fly above 120m without prior notification and authorisation from the GCAA.
7. Unmanned aircraft operations should be performed within the visual line-of-sight (VLOS) of the operator. This means there should be a direct unobstructed path between the eyes of the operator and the UAV whether it is airborne or on ground. Operators must attain prior authorisation from the GCAA in order to perform UAV operations beyond visual line-of-sight.
8. All private and recreational drones must be flown below 120m (400ft) ASL.
9. No UAV must be operated within a 10-kilomtre radius from an airport or a helipad unless the operators seek authorisation from the GCAA. In the case where a UAV must operate within this radius, prior permission must be sought from the GCAA. It would also be necessary to seek further authorisation from the airport's management and Air Traffic Control (ATC).

10. Drones are not permitted to fly within a 30-metre radius of buildings or vehicles.
11. No UAV is permitted to operate at night without prior authorisation from the GCAA.
12. No individual or organisation is permitted to import, export, sell or operate RPAS or any parts of RPAS without receiving prior authorisation from the GCAA.
13. No individual or organisation must manufacture an RPAS or parts of it without the written permit of the GCAA.
14. All UAV operators must conform to the noise control, emissions and privacy regulations.
15. Permissions granted by the GCAA to a UAV operator does not relieve that operator of his/her responsibility to adhere to the regulations of other Government bodies. Take for example, you are a UAV operator in an institution that has been tasked with mapping out an area 500m away from the Kotoka International Airport. And as part of your preparations for the operation you submit a request to the GCAA of your intent to perform such an operation one month ahead of the intended date of operation. In your request, you described the necessary details of the intended operation including the date and time. If upon perusal of your proposal, the GCAA decides to grant you the permission to undertake the operation, it does not relieve you of your obligation to inform the management of Kotoka International Airport of your intention. Failure to do so would violate the airport's drone restriction policies and result in legal implications for the operator.
16. No one is permitted to perform maintenance for a large RPAS without the approval of the GCAA. Also, any maintenance performed by an authorised organisation, must be done in accordance with the UAV manufacturer's maintenance requirements.
17. Any group, club or association formed to promote, use or operate RPAS must notify the GCAA of its existence in writing within three months of its formation.

Exemptions from the GCAD Part 28

The Ghana Civil Aviation Directive (GCAD) Part 28 sets out the requirements for the operations of unmanned aircraft including model aircraft. All unmanned aircraft, whether remotely-piloted, fully autonomous or combinations thereof are subject to the provisions of this Directive. However, the GCAD Part 28 does not apply to the following:

1. A manned balloon or hot air balloon
2. A control-line aircraft (that is, a model aircraft that is constrained to fly in a circle and is controlled in attitude and altitude, by means of extensible wires attached to a handle held by the person operating the model)
3. An aircraft indoors
4. An unmanned airship indoors

5. A small balloon within 100metres of a structure and not above the top of the structure
6. An unmanned tethered balloon that remains below 400 feet AGL.

Special Authorisation

All the rules discussed thus far are general and operators must always comply with them. There are however some cases of interest that require special authorisation from the GCAA, and even sometimes other governmental agencies. In such cases, the operator must seek permission from the GCAA and any other relevant bodies before carrying out the operation. According to the GCAD Part 28:

1. No person shall operate an RPAS in the following operations without special authorisation from the GCAA:
   a. The carriage of goods
   b. The carriage of dangerous goods
   c. Night operations
   d. Banner towing
   e. Cross border operations:
      This means that for any operation that requires a UAV to fly beyond the boundaries of Ghana into the airspace of other countries, special authorisation must first be sought from the GCAA. For such an operation, border agencies like the Ghana Customs Division and the Ghana Boundary Commission may need to be informed prior to the operation.
   f. Hazardous operations
   g. Dropping and discharging of things
   h. Acrobatic, formation and racing flights
   i. Operations in restricted areas
   j. Operations in areas of high RF transmission/interference (e.g. radar sites, high tension wires).
2. A request for special authorisation shall be made in a form and manner as prescribed by the Authority (GCAA).
3. The request for authorisation shall be made not less than thirty days before the date of intended operation.

Rpa Registration and Permit Issuance

Any prospective UAV operator in Ghana is required by law to first undergo UAV training with a GCAA approved RPAS training organisation. The training involves the technicalities of flying the particular type of UAV the trainee would want to operate and education on the RPAS regulations of the GCAA. Undergoing UAV training with any institution that is not certificated by the GCAA to provide training services is prohibited and any certificate or endorsement from that institution is not recognised by the GCAA. The individual, after being trained by a GCAA-accredited RPAS training organisation, the individual must be examined by a GCAA official before being granted a pilot's license. Once granted, the individual is legally permitted to operate the UAV for which he/she has been trained to operate. The license, however, must be renewed yearly to maintain validity. Also, all UAVs in Ghana must be registered by the GCAA and insured (by an insurance service provider) before being permitted to operate.

Classification of RPAS

Unmanned aircraft systems are classified by the GCAA into 3 main categories based on their mass. The classes are:

1. **Small RPAS:**

   This refers to unmanned aerial vehicles with maximum take-off mass of 1.5kg or less. They are only permitted to be flown within the visual line-of-sight of the UAV pilot. These aircraft are typically small in size and generally unsophisticated although there are some exceptions. For example, the DJI Phantom 4 RTK drone has a take-off mass of 1.391kg, and hence falls into the category of small RPAS.

Figure 6.1: DJI Phantom 4 RTK (DJI представила Phantom 4 RTK)

2. **Light RPAS:**

   This category consists of unmanned aerial vehicles with maximum take-off mass of more than 1.5kg, but not more than 7kg. These unmanned aerial vehicles are also restricted to operate within the visual line-of-sight of the UAV pilot. The **Figure 6.2** below shows the Believer fixed-wing UAV which has a maximum take-off mass of 5.5kg. This UAV is in the light RPAS category.

Figure 6.2: Believer UAV (Believer – en.makeflyeasy)

3. **Large RPAS:**

   This refers to unmanned aircraft with a maximum take-off mass of more than 7kg. These aircraft may be flown within visual line of sight or beyond visual line-of-sight when prior authorisation is obtained. Most sophisticated long endurance UAVs are in this category. The F320 VTOL drone for example, falls into the large RPAS category. This is because it has a maximum take-off mass of 23kg.

Figure 6.3: FW320 VTOL UAV (Long Endurance VTOL Drone | 23KG MTOW | 2.5Hours Endurance)

Activity 6.1

Safety Precautions Regarding UAV Operations

1. In pairs, read through and discuss the definitions (from pages 8 to 16) and general guidelines for RPAS operation (on pages 6 and 7) of the GCAA Directive Part 28 at PART_28_REMOTELY_PILOTED_AIRCRAFT_SYSTEMS_DIRECTIVES.pdf

2. In your pairs, discuss the classes of UAVs.
   Identify possible uses for each of the different weight classifications of UAVs.
3. In your pairs, brainstorm the reasons behind the recommended safety precautions regarding UAV operations.
4. Create a poster highlighting the reasons you have identified for the recommended safety precautions for UAV operations. Present this poster to your class for discussion and feedback.

Test yourself!

1. What are the classes of UAVs? What are their weight ranges?
2. What is the maximum allowable operational ceiling for UAVs?
3. How far from aerodromes are UAVs allowed to operate?
4. What does BVLOS mean, and which class of UAVs are allowed by the GCAA to do BVLOS operations?

UAV Operation Safety

Although UAV integration into our lives has simplified previously difficult or almost impossible tasks, they can be dangerous if not used responsibly. It is hence very important to reduce UAV operational risk to the minimum. We shall discuss some guidelines to consider in order to reduce the risk that UAVs pose to operators, bystanders and property.

1. The operators must first be trained and certificated on how to operate the particular type of UAV. They must have the know-how to keep the drone in good working conditions and identify faults and anomalies in the RPAS if any arises.
2. Before flying a UAV, it is important to attain knowledge on the terrain, tree cover and types of structures in the environment from which the UAV will be launched, as well as all its stop locations. This will inform the operator on how to plan the operation, what to look out for and even the type of UAV that will be best suited for the operation. For example, if a forest area is to be mapped, it would be prudent to know the nature of the forest floor. Is the floor a slope or fairly flat? Is there a decent clearing to setup the ground control station? What is the average height of the tallest trees and what should be the operation altitude of the mission? If the intention is to map the area with a fixed wing drone, will the drone have a clearing to take-off and land? Should I consider using a multi-rotor or a fixed-wing with VTOL capabilities? These are some questions that proper assessment of the mission area will help the operator solve. Poor assessment or failure to assess the mission area can lead to loss of the drone, damage to property or injury to people.
3. Power lines are very easy to miss because they are thin and may not be very conspicuous at a distance. Note the locations of all surrounding power lines and ensure there are no power lines in the planned flight paths. Communication towers must also be looked out for. Flights near communication towers should be avoided as much as possible as the radio waves can disrupt the command-and-

control link between the remote-pilot station (RPS) and remotely-piloted aircraft (RPA).

4. Secure the approval of the GCAA and any other relevant body. This is to ensure all relevant bodies are aware of the operation.
5. All batteries for the drones, the remote-pilot station should be charged a day ahead of the flight. Ensure the batteries are in good shape and no cells are damaged. A cell tester or digital multimeter may be used for this. In the case where a battery is charged a day ahead of the intended flight day, but the flight is later called off, the operators must ensure that batteries are discharged to appropriate voltage levels as indicated by the manufacturer using equipment recommended by the battery manufacturer. This is because keeping batteries fully charged for a long time causes them to fail and this failure may occur in-flight.
6. After gathering the necessary pre-flight information, the flight should be planned taking into account the terrain, physical features of the take-off site, technical limitations of the UAV specified by the manufacturer, weather forecast and operational confines set by the GCAA. It is also prudent to consider the input of relevant governmental bodies and other stakeholders.
7. The remote-pilot station should be installed at a proper location and must be well sheltered from direct exposure of the weather elements like direct sunshine, rain or wind. It is recommended to have a shed or tent under which the RPS and its components can be sheltered.
8. The RPS should be setup according to the guidance outlined by the manufacturer. Keep track of all the components that make up the RPS. Ensure the RPS behaves in a predictable manner and there are no abnormalities.
9. Remove liquids from the immediate environment of the RPS as they pose the risk of spillage which may cause damage to equipment.
10. Be mindful of polarity when installing batteries. This is not an issue with most small consumer drones as their batteries are designed to fit in a particular way and will not fit when reversed. However, with industrial drones that use off-the-shelf LiPo and Li-Ion batteries, this can cause serious complications if not checked.
11. Setup the RPA. Some RPAs are modular and must be assembled. Such RPAs should be assembled in accordance with the steps and guidelines of the manufacturer. Keep track of all the parts that make up the RPA and ensure nothing is left out of the assembly. Any part left out in the installation poses the risk of being a point of failure when the aircraft gets airborne. However, it is generally recommended (if possible) not to install the propellers until one is sure the aircraft behaves in a predictable and controllable manner.
12. Establish the command and control link between the RPA and RPS. Ensure the RPA responds in a predictable manner.
13. Propellers can then be installed after it has been ascertained that the RPA behaves in a controllable manner. Propeller installation should be done with scrutiny. Ensure clockwise (**cw**) propellers are mounted on rotors that spin in the clockwise and counter-clockwise (**ccw**) propellers go onto counterclockwise rotors. Reversing

or flipping propellers can cause severe damage to the RPA and injury to persons around.

14. Perform a walk-around pre-flight inspection of the drone, inspecting and ensuring everything is in place. It is recommended to have a ***checklist*** to aid in this inspection.
15. Ensure there are no loose mechanical joints or electrical connections.
16. Do not go close to rotating propellers.
17. Have a fire extinguisher nearby or a bucket of sand.
18. Ensure there is constant communication between the RPA and RPS throughout the duration of the flight.
19. Remember to set necessary failsafe responses on the UAV.
20. After any UAV operation, perform a post-flight inspection of the drone. Wipe off dust and debris on the UAV while looking out for dents or nicks on the airframe and propellers.

Benefits of Adhering to Safety Precautions

In spite of the efforts put in place to ensure operational safety when dealing with drones, they can still pose a risk of injury to the operators and bystanders. It is therefore very vital and beneficial to ensure that the right safety precautions and recommended practices are enforced during operations. Adherence to safety precautions ensures a productive, safe and secure working environment. Let us explore some benefits derived from adhering to safety precautions:

1. **Prevention of Accidents and Injuries:**
   Perhaps the most obvious and important reason for putting safety measures in place is to minimise the risk of accident to the barest minimum. Possible accidents include liquid spillages, fires, equipment malfunctions and structural failures.

   Let's look at an example of how adherence to safety precautions prevents accidents and injuries. When a propeller is spinning, it is subjected to centrifugal forces, like all spinning bodies. This centrifugal force acts in an opposite direction away from rotational axis of the propeller. This puts the propeller blade in tension and tries to "tear" the blade of the propeller from the hub. It is therefore important for the propeller to be strong enough to withstand this centrifugal force. If the structural integrity of a propeller is compromised, this centrifugal force may break off the propeller and cause injury to the crew or others around. It is therefore important for the drone to be operated no less than 30 metres away from people and buildings. And also the crew must regularly check propellers for nicks or cracks and wear appropriate PPEs, especially eye protection when working with drones.

2. **Ensures Compliance with Regulations:**
   The core reason for GCAA's RPAS guidelines is to ensure safety in UAV operations hence adhering to safety protocols ensures compliance with regulations. Failing to comply with these regulations may attract legal issues and potential fines.

3. **Protects Equipment and Facilities:**
   Some equipment used in RPAS operations cost a fortune and hence keeping safety standards and recommended practices keeps equipment in proper working condition and protects them from damage.

4. **Enhance productivity:**
   A safe working environment provides a sound avenue for professionals to conduct proper operations. It enhances the flow of work and prevents possible downtimes caused by accidents and equipment failures.

5. **Fosters a Positive Work Environment:**
   Making safety a priority in the workplace creates a prolific working environment and fosters a culture of care and responsibility which improve morale and create work satisfaction.

6. **Facilitates Training and Skill Development:**
   Safety standards provide an organised framework for upskilling new personnel. It provides a structured guide to help novices understand and follow recommended practices and procedures to enhance safety in a working environment.

7. **Mitigates liability:**
   Any operational accident leads to some form of liability to individuals or organisations. These liabilities may be in the forms of hospital bills for injury treatment, replacement cost for damaged properties and equipment, as well as downtime. Proper safety practices reduce the risk of accidents and the liabilities that are associated with them. This protects the individual and organisations from financial losses.

8. **Supports Emergency Preparedness:**
   Adhering to safety protocols enhances the readiness of operators. It ensures the swift and effective response of operators in implementing emergency procedures in the case of an incident or accident.

Importance of observing UAV regulations

Unmanned Aerial Vehicles (UAVs) are gradually becoming integral parts of the operations of several industries like agriculture, surveillance, remote sensing, recreation, security and defence, mineral exploration, oil and gas exploration and logistics. This growing use of drones necessitates the regulation of the air space by civil aviation bodies. Below are some reasons why UAV operators must comply with civil aviation regulations.

1. **Safety**
   a. **Airspace Safety**: UAVs and manned aircraft use the same airspace. One important benefit of UAVs is that they carry no humans on board, however, manned aircraft do. It is therefore important for air traffic and air space regulations to be adhered to by both manned and unmanned aircraft to avoid collision. For example, the Ghana Civil Aviation Authority restricts drones to a maximum operational altitude of 120m above ground level. Hence, any drone

flying above 120m risks colliding with a manned aircraft. In view of this, it is required by law for drones to operate within their GCAA-designated airspace to enhance safety.

b. **Ground Safety**: UAVs not only pose operational risk when they are airborne. For this reason, civil aviation bodies typically impose proximity limits on operational drones to humans and property. For example, the GCAD Part 28 requires that drones do not operate within a 30m radius from a group of people or buildings (GCAD Part 28, 28.10.7). This is to safeguard nearby people, buildings and the drone itself from injury or damage should the drone malfunction.

2. **Privacy and Security**

a. **Privacy Protection:** Due to the boom in consumer drones, many individuals have the means to buy drones with camera payloads capable of transmitting and recording video footage while airborne. Therefore, in order to prevent the invasion of personal spaces and properties of individuals or organisations, civil aviation bodies regulate the operation of consumer drones. It is for such a reason that civil aviation bodies mandate drone operators to seek the approval of relevant bodies when conducting drone operations.

Figure 6.4: A drone with a camera payload (DJI Air 2S Melds Incredible Image Quality With Unmatched Flight Performance – sUAS News)

b. **National Security:** Modern warfare has been revolutionised by drones. Drones are capable of carrying explosives and releasing them at specified locations. Others, popularly known as loitering-munition drones carry explosive payloads and fly into pre-determined targets before exploding to take out the target, destroying the drone and the target in the process. It is therefore a national security concern in monitoring the drones that come into the country. It is also important for national security agencies to have data to refer to concerning the UAVs flying within the nation's borders. This is to prevent terrorist and insurgency groups from using such technology to cause harm.

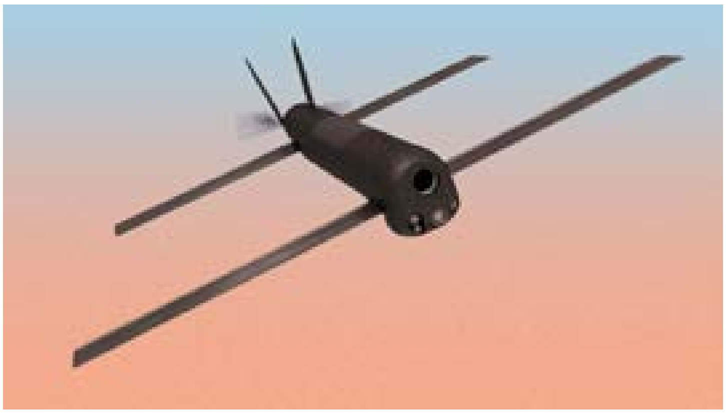


Figure 6.5: The Switchblade loitering-munition drone by Aerovironment (What to know about the «kamikaze» drones the U.S. is giving Ukraine)

3. **Legal Compliance**

   a. **Avoiding Legal Consequences**: Non-compliance with the GCAA UAV regulations can attract fines, legal actions and potential confiscation of drones. Adhering to the regulations ensures that UAV activities are lawful and transparent.

   b. **Insurance and Liability**: Before drones are registered with the GCAA, they must be insured first. Many insurance policies require that operators follow UAV regulations. Non-compliance often results in the voiding of insurance coverage and increased liability in case of accidents or damages.

4. **Industry Credibility**:
   Adhering to regulations enhances the credibility and professionalism of UAV operators, fostering trust and acceptance from the public and stakeholders. A clear regulatory framework supports the sustainable growth of the UAV industry by providing guidelines for safe and responsible use, encouraging innovation within defined boundaries.

Activity 6.2

Mapping Out

The map below depicts a section of Accra. You are to map out the area within the red square as shown on the map using a drone. Kotoka International Airport (KIA) is 9.75km from point X on the map. The yellow line on the map is an extension of the centre line of the runway at KIA. That is, if an aircraft is to take-off from KIA and fly straight without turning, the yellow line traces its flight path. As a UAV operator, document a plan you would assume to undertake such a mission from start to finish while adhering to regulations. Use the following questions as a guide:

1. Which institutions or bodies must be informed about the operation?
2. Which authorisations must be sought?

3. How does following safety guidelines affect the operation?
4. Are there no-fly-zones in the designated area?
5. Should special authorisation be sought?
6. How far is the site from the nearest aerodrome? Will the mission be in the take-off or approach path of the aircraft from this aerodrome?

Figure 6.6: Map of an area in Accra

Activity 6.3

Safety Operating Procedures of UAVs

1. Join a school visit to the GCAA RPAS office to interact with their staff, discussing with them the regulations regarding UAV operations and personnel licensing. Take notes of these discussions and share what you learnt later in a classroom discussion.
2. If a visit is not possible, undertake this alternative activity:
   a. In a small group, with the aid of these online videos and a practical session with a UAV in the Aerospace Laboratory, discuss the safety operating procedures of UAVs.
      - SOPs UAVs 1
      - SOPs UAVs 2
      - SOPs UAVs 3
      - SOPs UAVs 4

b. Discuss the reasons behind the stipulated safety guidelines.

Test yourself!

1. List 5 areas that are designated by the GCAA as no-fly-zones in Ghana.
2. Discuss 3 safety hazards that drones may pose to society.
3. Discuss 5 general GCAA RPAS guidelines.

INTEGRATING SIMULATORS TO ENHANCE UAV OPERATIONS SAFETY

Introduction to UAV Simulation

UAV simulators are software or virtual platforms designed to replicate the experience of piloting drones in a controlled environment free of risk. These tools are widely used for training purposes, allowing new and experienced pilots to practice flight manoeuvres, learn regulations, and improve skills without the risk of damaging real drones or violating safety guidelines. In general, there are many types of flight simulators tailored for various purposes. There are simulators designed to be used for training on specific manned aircraft and those purposely made for UAVs. They range from simple software running on computers to a system of embedded hardware, software and mechanical actuators.

Figure 6.7: Exterior of the Boeing 787 simulator (Boeing-flight-simulator-2 - Pilot Career News : Pilot Career News)

Figure 6.8: Inside view of Boeing 787 Simulator (Aeromexico Inaugurates The New Boeing 787 Simulator. Aeromexico Mexico)

However, they all comprise a system that physically takes in pilot inputs by means of buttons, dial or control sticks, converts those inputs into electronic signals for processing and giving output through graphics, sound or mechanical actuation. This section will primarily focus on drone simulators. Let us now look at some features of drone simulators.

1. **Realistic Physics Environment**: This is the backbone of simulators. This is comprised of a computer program that makes use of real-world physics and equations of motion aircraft to compute and predict the manner in which an aircraft responds to pilot input and environmental factors like the wind. It mimics a drone's flight dynamics, weight distribution, aerodynamics, propulsion and avionics, among others. They account for environmental variables like wind speed and direction, turbulence and altitude. Without a good physics environment, the simulator will not closely mimic real-world conditions and hence will be no different from an ordinary video game.

2. **Training Modules**: Simulators usually come with pre-designed scenarios for specific training objectives. They provide training courses for beginner pilots to learn how to take-off, perform basic flight manoeuvres and land. They may also feature training modules that teach how to respond to emergency situations and how to perform specialised tasks like precision landing. In many cases these modules are timed and scored to keep the training engaging and goal-oriented.

3. **Varied and Customisable Drones:** Many simulators allow users to choose from a wide variety of aircraft with various features. This is particularly useful because there is usually a high probability of finding an aircraft that is similar to, if not exactly the same as, what a user wants. Another interesting feature is that some drone simulators allow users to adjust some features of selected drones to suit their needs or flying styles.

4. **Varied Simulation Environments and Emergency Situations:** One major reason why simulators are so useful is their ability to mimic real-world conditions without associated liabilities. Many simulators allow the users to tweak environmental conditions in the virtual environment to simulate emergency

situations like engine failures, structural failures, strong crosswinds while landing and many others. This gives trainees the opportunity to practice how to handle emergency situations without having to actually damage a UAV. Most simulators also feature multiple flying environments to give trainee pilots the experience of flying in various environments.

Components of Flight Simulators

Flight simulators are comprised of mechanical, electronic and software components. The diagram below shows the block diagram for a simple flight simulator. Let us now look at the major `components in the flight simulator system.

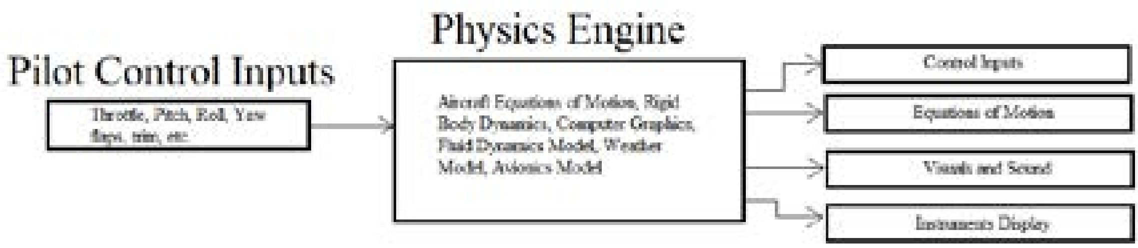


Figure 6.9: Basic block diagram of a UAV flight simulator

Pilot Control Inputs

Drone flight simulators take their control inputs from controllers, which usually connect to computers via USB. They come in different shapes and sizes, each with its benefits. Two main types of simulator controllers stand out as the most popular. They are the handheld "gamepad-style" controller and the yoke-style controller. The yoke-style controller is mostly designed to be used for aeroplanes and helicopters, while the gamepad-style is used for all types of aircraft.

Controllers are usually classified according to the number of channels they have. A channel in this context refers to the number of independent inputs that the controller allows the pilot to send into the simulator at a time. For example, a four-channel controller would only allow the user to control four things at a time. These may be roll, pitch, throttle and yaw. If the aircraft has flaps in addition to the primary control surfaces, the user will have to replace the controller with one that has five channels or more.

Figure 6. 10: Drone simulator controller by Interlink [InterLink DX Simulator Controller with USB Plug | Spektrum (spektrumrc.com)](https://www.spektrumrc.com/product/interlink-dx-simulator-controller-with-usb-plug/SPM-RFTX1.html) https://www.spektrumrc.com/product/interlink-dx-simulator-controller-with-usb-plug/SPM-RFTX1.html

Figure 6.11: Thrustmaster Simulator Controller Manche Joystick Thrustmaster T.flight Hotas X Pc Original | Frete grátis (mercadolivre.com.br)

Control Modes

There are four main control modes controllers (for both RC and simulator) on the gamepad-style controller. For each mode, the movement of each stick is mapped to a specific function. For example, on a mode 2 controller, moving the right control stick up and down controls the elevator. Technically, there can be numerous ways combinations to map stick movements to specific actions on a drone. However, the modes create a standard that pilots can use to learn and teach others. No mode is better than the other because it mostly comes down to each pilot's preference.

Figure 6.12: Mode 1

Figure 6.13: Mode 2

Figure 6.13: Mode 3

Figure 6.14: Mode 4

Source : RC Transmitter Modes for Aeroplanes (rc-airplane-world.com)

The most common of these configurations is MODE 2. However, it is best to not assume that every drone is to be flown in mode 2. The best course of action when handling any drone for the first time is to ask from the previous user the mode in which the drone was last flown. If you are not certain, then remove the propellers and manually figure out the mode by moving the control sticks and observing the response on the aircraft. Some popular flight simulators are RealFlight, Picasim and DRL simulator.

Software-In-The-Loop (SiL)

Generally speaking, software-in-the-loop is a method of testing system of algorithms or entire control loops on a computer without the hardware. This method is commonly used to test robotics systems. Certain drone simulators allow users to perform software-in-the-loop. For example, one can use RealFlight simulator and Mission Planner GCS to simulate the performance of Ardupilot firmware (a firmware for drones) and execute operations in various in-flight modes.

The actions of the drone are displayed, along with performance indicators, in a 3d graphical environment. This enables the user to test different flight modes and scenarios, execute planned missions, identify errors and challenges and correct them without having to test on an actual UAV which may compromise safety and raise financial concerns. It also helps in the research and development of new and unconventional UAVs. They are tested and fine-tuned on the simulators where they pose no danger to life and property, before being implemented in the real-world.

Importance of Drone Simulators

Drone simulators are vital tools for individuals and organisations involved in unmanned aerial vehicle (UAV) operations. By replicating real-world flying conditions, simulators provide a risk-free, cost-effective, and accessible platform for training and skill development. Here are the key reasons why drone simulators are important:

1. **Safety Enhancement:**Simulators allow users to practice piloting drones without the risk of accidents, injuries, or property damage. They are particularly valuable for training on emergency scenarios, such as signal loss, battery depletion, or adverse weather conditions, which would be unsafe to replicate with real drones.

2. **Cost-Effective Training:** Learning to operate drones in a simulator eliminates the expenses associated with real-world training, such as replacing damaged equipment, renting training spaces, or purchasing consumables like batteries. Simulators also save costs by avoiding damages, injuries and potential fines for regulatory violations during training.
3. **Skill Development:** Simulators cater for beginners learning basic controls and advanced users practicing complex manoeuvres or professional applications. They provide a controlled environment to develop precision skills, improve reaction times, and build confidence before transitioning to real drone operations.
4. **Regulation Familiarisation:** Many drones allow users to integrate airspace regulations like no-fly-zones and altitude limits. This allows users to learn and comply with UAV regulations.
5. **Preparation for Specialised Applications:** Professionals in industries such as agriculture, surveillance, infrastructure inspection, videography, and search-and-rescue benefit from simulators tailored to their needs. For example, they can practice missions like crop monitoring, mapping or bridge inspections before executing the mission in the real-world. This allows them to make plan and make adjustment before executing the operation.
6. **Fostering Research and Development:** Simulators like RealFlight, allow users to create their own aircraft and fly in the simulator's environment. It also allows for the testing of new ideas and concepts. This enables researchers to quickly test a concept and fine tune it in a virtual environment in a safe and cost-effective way.

Basic Drone Piloting

It is important for a drone pilot to know the basic controls for the type of UAV they operate. We shall consider the basic controls of multicopter UAVs. For the purpose of conceptual understanding, we will use the quadcopter to explain the basic manoeuvres. Since mode 2 configuration is the commonest, it would be used here. However, one should be mindful that not all drones may be configured to be piloted in mode 2 and hence prior information concerning the mode should be sought before attempting to fly any drone.

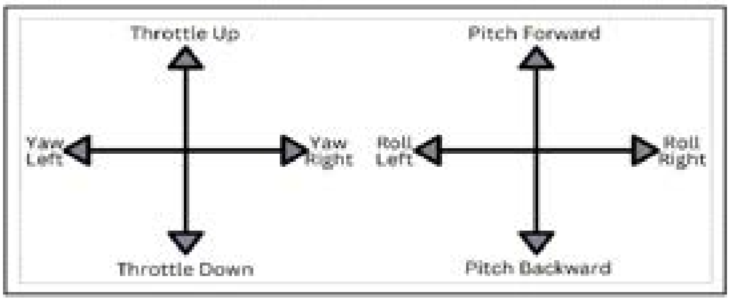


Figure 6.15: Controls in Mode 2 (https://www.droneblog.com/wp-content/uploads/2023/07/stick-inputs.png)

Introduction to multirotor piloting

Roll

This is achieved by pushing the right stick to the left or right. With reference to the image of the quadcopter below, moving the right stick to the right will increase the RPM of the motors on the left (3 and 4), thereby increasing the lift they generate and causing the drone to tilt to the right. If the right stick of the controller is moved to the left, the RPM of the motors on the right (1 and 2) will increase, causing the drone to tilt and move to the left.

Pitch

Pitch is controlled by pushing the right stick upwards or downwards. Moving the right stick upwards causes the RPM of the motors at the rear (2 and 3) to increase, thereby causing the drone to tilt and move forward. Conversely, moving the right stick downward causes the motors at the front (1 and 4) to increase RPM, causing the drone to tilt and move backwards.

Yaw

By convention (generally accepted or common norm), motors 1 and 3 rotate in the counterclockwise direction, while motors 2 and 4 rotate in the clockwise direction. The reason is that if all the motors rotate in one direction (say clockwise), then the drone's frame will tend to spin in the opposite direction (counterclockwise). This phenomenon draws from Newton's third law of motion. That is, a clockwise spinning action will result in a counterclockwise spinning reaction and a counterclockwise spinning action will yield a clockwise spinning reaction.

The yaw manoeuvre (in mode 2) is done by moving the left stick left and right. In order for the drone to yaw left, the clockwise motors spin faster than the counterclockwise. This produces a counterclockwise reaction moment on the airframe of the drone causing it to yaw left. In the same way, if the counterclockwise motors spin faster than the clockwise motors, a clockwise reaction moment is created causing the airframe to yaw right.

Figure 6.16: Movement of a quadcopter (https://www.tdrones.com/images/202404/231713860873887044.jpeg)

Activity 6.4

Flight Manoeuvring

1. Using a flight simulator installed on a computer (personal or a lab computer), perform the following basic flight manoeuvres on a quadcopter:

   a.

   i. Take-off
   ii. Pitch forward
   iii. Pitch backwards
   iv. Increase altitude
   v. Reduce altitude
   vi. Roll left
   vii. Roll right
   viii. Yaw left
   ix. Yaw right
   x. Land

   b. Manoeuvre such that your drone traces a vertical rectangle while airborne.

   c. Perform a manoeuvre in which your drone traces a horizontal rectangle.

2. Perform the following manoeuvres in a simulator using a fixed-wing aircraft:
   a.
      i. Take-off
      ii. Pitching
      iii. Rolling
      iv. Yawing
   b. How does the fixed-wing aircraft behave when you try to fly it at very low speeds? Write down your observation and explain why it behaves that way.
   c. Write down the difference between fixed-wing and quadcopter controls you noticed.

Test yourself!

1. Write down four reasons why you think flight simulators are important to the UAV industry.

EXTENDED READING

- Introduction to ICAO Model UAS Regulations and Advisory Circulars https://www.icao.int/safety/UA/Pages/ICAO-Model-UAS-Regulations.aspx
- Drones Across the World – Laws and Policies by Sarah Nilsson, PhD, JD https://eaglepubs.erau.edu/dronesacrosstheworld/front-matter/introduction/

Review Questions

1. What is the maximum allowable operational altitude for UAVs in Ghana?
2. Write down three benefits of adhering to UAV regulations.
3. Which class(es) of UAVs are permitted by the GCAA to do only VLOS operations?
4. Discuss four important reasons for observing proper safety protocols.

APPENDIX A FOR SECTION 1

International Standard Atmosphere Table

Altitude (km)	Temperature (K)	Pressure (Pa)	Density (kg/m^3)
-0.5	291.4	107477	1.285
0	288.1	101325	1.225
0.5	284.9	95461	1.167
1	281.7	89876	1.112
1.5	278.4	84559	1.058
2	275.2	79501	1.007
2.5	271.9	74691	0.957
3	268.7	70121	0.909
3.5	265.4	65780	0.863
4	262.2	61660	0.819
4.5	258.9	57752	0.777
5	255.7	54048	0.736
5.5	252.4	50539	0.697
6	249.2	47217	0.66
6.5	245.9	44075	0.624
7	242.7	41105	0.59
7.5	239.5	38299	0.557
8	236.2	35651	0.526
8.5	233	33154	0.496
9	229.7	30800	0.467
9.5	226.5	28584	0.44
10	223.3	26499	0.414
10.5	220	24540	0.389
11	216.8	22699	0.365
11.5	216.6	20984	0.337
12	216.6	19399	0.312
12.5	216.6	17933	0.288
13	216.6	16579	0.267
13.5	216.6	15327	0.246
14	216.6	14170	0.228
14.5	216.6	13100	0.211
15	216.6	12111	0.195
15.5	216.6	11197	0.18
16	216.6	10352	0.166
16.5	216.6	9571	0.154
17	216.6	8849	0.142

17.5	216.6	8182	0.132
18	216.6	7565	0.122
18.5	216.6	6994	0.112
19	216.6	6467	0.104
19.5	216.6	5979	0.096
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GLOSSARY

A

Absolute pressure – A pressure measurement taken with respect to a vacuum

Aero**drome –** a location from which aircraft flight operations take place

Air navi**gation services –** services that support air traffic throughout all phases of its operations, ensuring that aircraft pass safely and efficiently through the airspace

Amplitude – The maximum displacement of an entity from its equilibrium position

Attitude – The orientation of an aircraft, often expressed as roll, pitch and yaw angles

Avionics – Electronic systems related to aircraft or spacecraft

B

Bearing – An angle that describes the position of one body relative to another

Biofuel - A biofuel is a type of renewable energy source derived from organic materials, such as plants, agricultural waste, or animal by-products.

C

Civil aviation – the category of flying that includes all non-military and non-state aviation, such as private and commercial flights

Combustion – Combustion is the chemical process of burning a substance in the presence of oxygen to release energy, typically in the form of heat and light. It is a type of exothermic reaction, meaning it releases more energy than it absorbs.

Compliance – the act or process of adhering to a regulation

D

Down-time - Downtime in an operation refers to the period during which a machine, system, or process is not functioning or available for use.

E

eVTOL – Electric Vertical Take-off and Landing is a new trend in aircraft design where electric motors are used to provide vertical lift for small manned aircraft.

F

Flight crew – the group of people responsible for operating and controlling the aircraft in flight

Flight route - This is a planned path that an aircraft follows from its departure point to its destination.

M

Meteor - A body of matter from outer space entering the Earth's atmosphere and burning up due to friction with air molecules.

Mo**bility –** the quality or state of being able to move.

P

Precession – The slow movement of the axis of a spinning body around another axis due to a torque acting to change the direction of the first axis. A perpendicular force applied at a point on a spinning disc acts 90^0 further in the direction of rotation for this reason.

Propellant - Propellant refers to a chemical substance or mixture used to produce thrust in rockets.

Protrusion - refers to something that sticks out or extends beyond the surface of an object.

S

Stall – A condition where the wings of an aircraft stop producing lift, causing the aircraft to fall towards the ground

Swarming - Drone swarming refers to the use of multiple unmanned aerial vehicles (UAVs) operating together in a coordinated manner, often autonomously, to achieve a common objective.

T

Taper - refers to a gradual decrease in width, thickness, or size along the length of an object

To**rque** is a measure of the turning force on an object, like a bolt or a lever

U

Ultraviolet light - This is a form of electromagnetic radiation which lies between visible light and X-rays in the electromagnetic spectrum.

V

Vortex - is a spinning, spiralling flow of air or fluid that forms around a central point.