7 Read the passage below and answer the questions that follow.

Forces in Flight

Thrust, drag, lift, and weight are the four forces that act upon all aircraft in flight. Understanding how these forces work and knowing how to control them are essential to flight.

Lift is the upward force on the aircraft acting perpendicular to the wing. While an aircraft's weight is concentrated at the centre of gravity (CG), the lift occurs at the centre of pressure (CP). In the design of aircraft, the CG is fixed forward of the CP as shown in Fig. 7.1 in order to retain flight equilibrium. The tailplane of the aircraft helps to maintain the stability of the aircraft. It consists of a horizontal stabiliser with a fixed wing section and an elevator which could be adjusted to produce a vertical force acting on the rear of the aircraft's body. The vertical stabilizer consists of a rudder which could be maneuvered to produce a force to adjust the sideway movements of the aircraft.
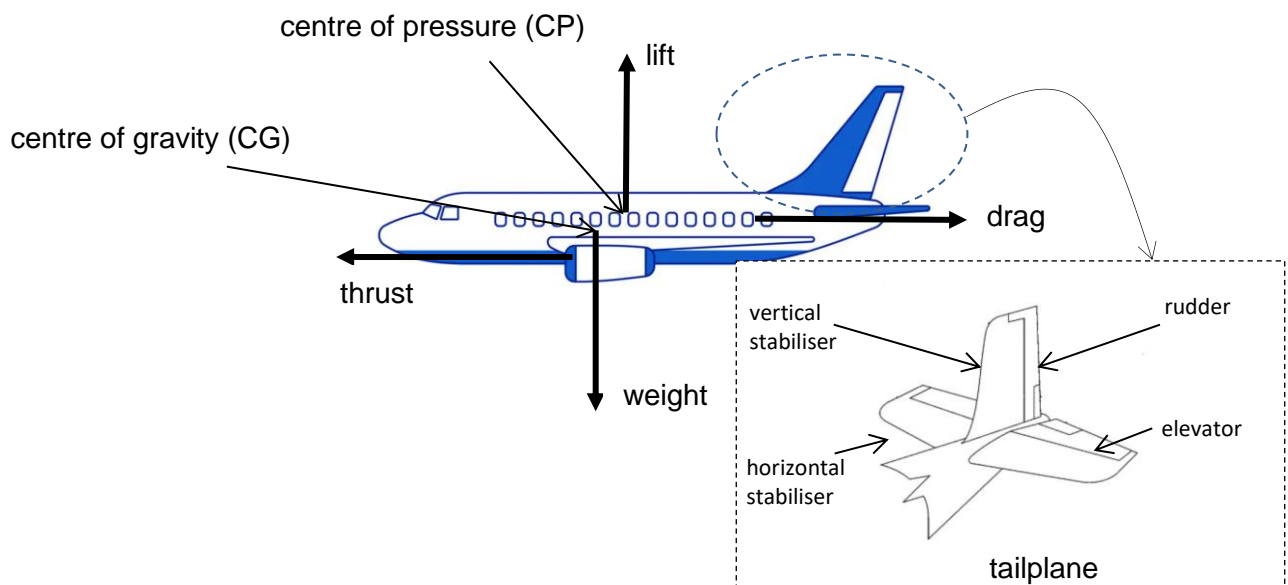

Fig. 7.1

The thrust is the forward force provided by a propulsion system of the plane – often the jet engines in a modern aircraft. A jet engine works by sucking air in the front, compressing it and then mixing and combusting the air with fuel before pushing it out at a much higher speed and higher pressure. Fig. 7.2 is a typical jet engine.
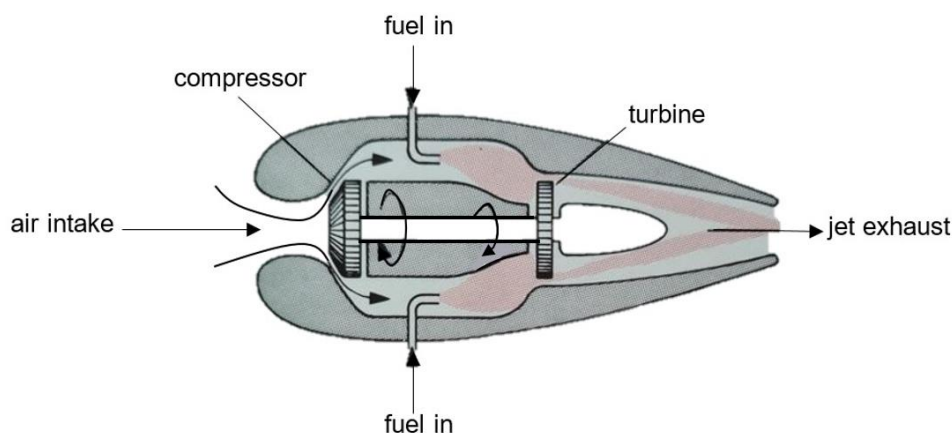

Fig. 7.2

Most of the lift of the aircraft is usually generated at the wings. The cross-section of the wings of the aircraft has a very special shape called an *aerofoil*. (Fig. 7.3(a)) The aerofoil looks like a teardrop that deflects the airflow downwards, increasing the velocity of the airflow on top and decreasing the velocity at the bottom. This effect produces a pressure difference between the top and the bottom of the wings which produces a net upward force known as the lift. By tilting the aerofoil at different angles with respect to the velocity of the air that flows through it, the lift force can also vary. This angle which the aerofoil makes with the velocity of the air that flows through it is known as the *angle of attack* α. (Fig. 7.3(b))

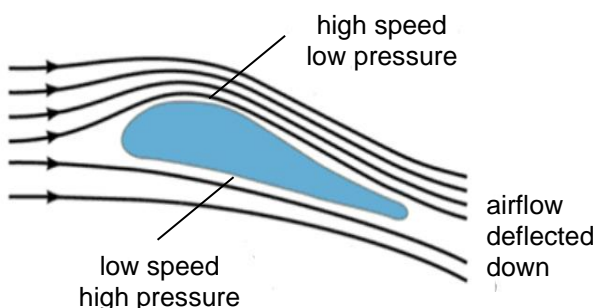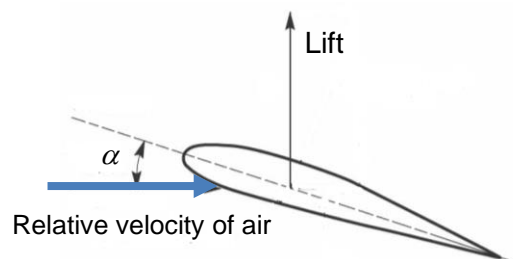**Fig. 7.3(a)**   **Fig. 7.3(b)**

Although a lift force is generated by the wing when it moves through the air, due to the viscosity of air, a drag force is also generated as an inevitable product of the lift. Apart from the wings, all other parts of an aircraft's airframe also generate a drag force which acts in opposite direction to the flight.

Both the lift (*L*) and the drag (*D*) forces depend on factors such as the shape of the aerofoil, angle of attack and the relative velocity between the air and the aircraft. These factors are taken into consideration in the following *Lift* and *Drag Equations* used by pilots to determine *L* and *D* :

Lift Equation : $L = \dfrac{1}{2}C_L \rho v^2 S$ and   Drag Equation: $D = \dfrac{1}{2}C_D \rho v^2 S$

where ρ is the density of the air, v is the relative speed between the aircraft and the wind and S the effective surface area of the wings. C_L and C_D are dimensionless constants known as the *lift coefficient* and the *drag coefficient* respectively. A dimensionless constant is one in which its unit is equal to one. Both C_L and C_D are dependent on the shape of the aerofoil and the angle of attack.

(a) An aircraft travels in a straight, level flight with a constant velocity as shown in Fig. 7.1. The total weight of the aircraft is 1.5 x 10^6 N, and the engines give it a forward thrust of 0.60 x 10^6 N.

(i) Determine the value of the lift and the drag.

lift = ...N

drag = ...N   [2]

(ii) The horizontal separation of the lines of action of lift and weight is 0.75 m. Determine the vertical separation of the lines of action of thrust and drag.

vertical separation = ...m   [2]

(iii) Due to the design of the aircraft, when the CG is forward of the CP, there is a natural tendency for the nose of the aircraft to tilt downwards when in flight.

Suggest how the tail stabiliser assists in maintaining the equilibrium of the plane.

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....[2]

(b) A simplified model of a jet engine of an aircraft is shown in Fig. 7.4.

Air enters at
an initial speed

Air exits at
a final speed

forward direction of aircraft

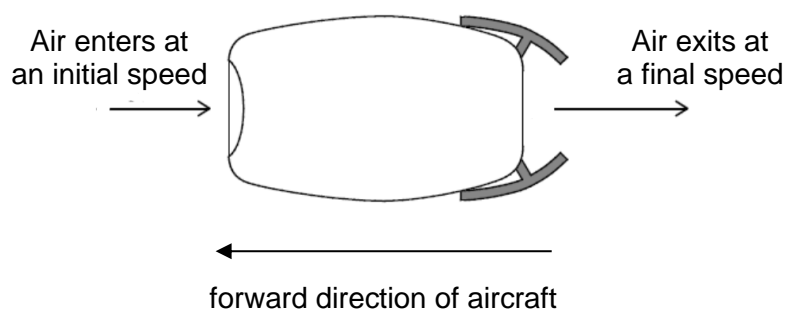**Fig. 7.4**

(i) By using Newton's Laws of Motion, explain how the air is able to exert a forward thrust on the engine.

[2]

(ii) For a particular flight, the mass flow rate of the air that enters the jet engine is 210 kg s^{-1} and this mass of air increases speed by 580 m s^{-1} as it passes through the engine.

Calculate the thrust provided by the air on this jet engine.

thrust = ...N [2]

(iii) In reality, the actual thrust on the engine is different from the value calculated in **(ii)**. Suggest a possible physics related reason for the difference.

[1]

(c) An aircraft has a mass of 2.85×10^5 kg and each wing has an area of 360 m². During level flight, the pressure on the lower wing surface is 7.00×10^4 Pa. Determine the pressure on the upper wing surface.

pressure = ...Pa [2]

(d) **(i)** Show that the coefficient of lift C_L is a dimensionless quantity.

[2]

(ii) To make a turn in flight, an aircraft often needs to do a tilt as shown in Fig. 7.5. Explain why the aircraft needs to tilt and increase in speed if it wishes to maintain the same altitude as before while making the turn.

Fig. 7.5

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....[2]

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[Question continues next page.]

(e) Both C_L and C_D are normally experimentally determined using a wind tunnel. Fig. 7.6 depicts the graphs of C_L and C_D with against the angle of attack α for a particular aerofoil wing; C_L is on the left axis and C_D is on the right axis. From these graph, the ratio of C_L to C_D can be found. This ratio is equal to the lift to drag ratio (*L/D*) which gives an indication of the efficiency of the performance of the plane in flight. A graph of some of the data showing the variation of *L/D* with α is shown in Fig. 7.7.
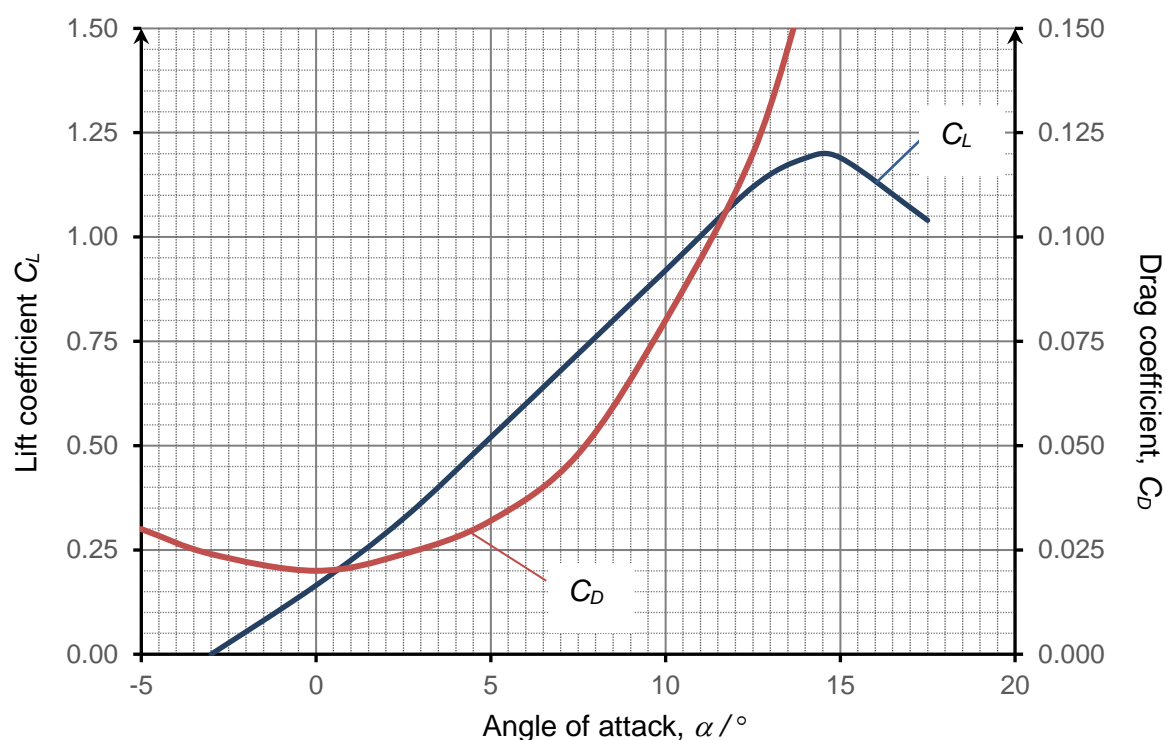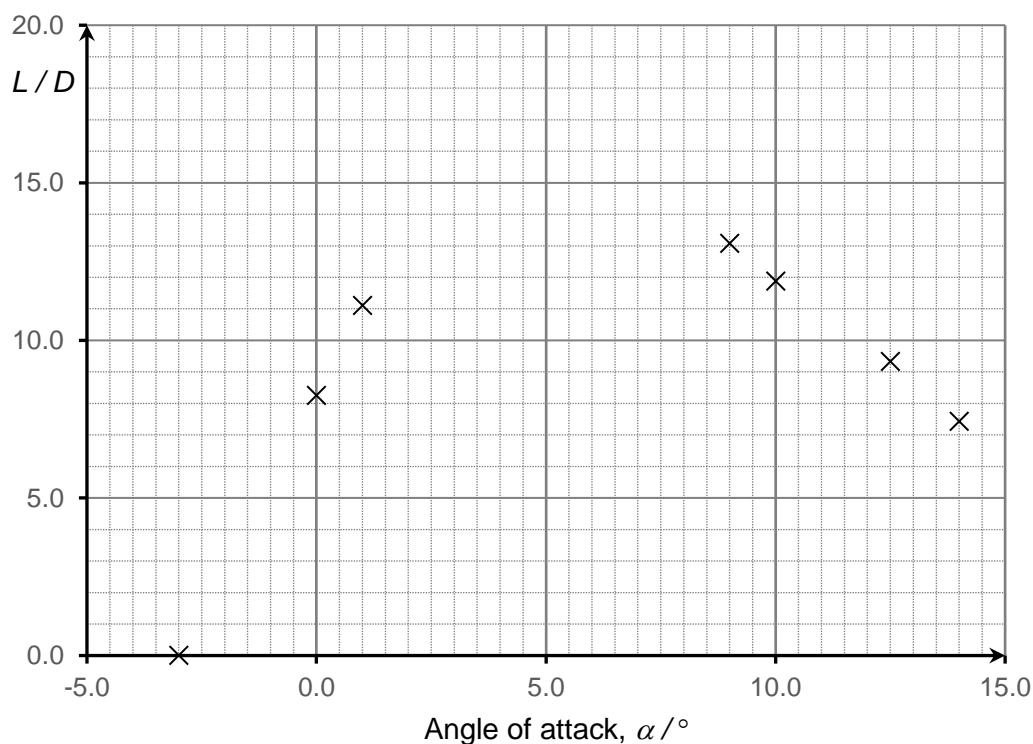

Fig. 7.6

Fig. 7.7

(i) Using the *Lift* and *Drag Equations*, show that the ratio of C_L to C_D is equal to the lift to drag ratio *L/D*.

[1]

(ii) In most phases of flight, the generation of lift is a distinct benefit, while the generation of drag is a distinct disadvantage. When the aircraft is at level flight, the wing is said to be working most efficiently when the lift to drag ratio is a maximum. Suggest why this is so.

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....[1]

(iii) For most conventional aerofoil wing, this greatest efficiency in **(e)(ii)** is achieved at an angle of attack at 4°.

1.   Using Fig. 7.6, determine the lift to drag ratio at this angle of attack for the aerofoil.

L/D = ...   [1]

2.   Plot this point on Fig. 7.7 and sketch the best fit curve.   [2]

[Total : 22 marks]

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