PART 1 : SECTION 1

CHAPTER 3

DRAG

Introduction

1. When an object is placed in a moving air stream, a force occurs which tends to move the object along the line of action of the air stream; it can also be said that if conditions were reversed and the object was moved through air at rest, the same force would be felt by the body. Irrespective of whether the air is moving and the body is stationary or vice versa, the force experienced on the body is the same. This force is known as *drag*.

2. An aircraft in steady level flight experiences an inherent total drag which must be balanced by the thrust from the engine or propeller. For a given engine power the amount of drag determines the speed of the aircraft. The efforts of the designer are concentrated on decreasing the amount of drag, and to do this the source of drag must be found and eliminated as far as possible. Drag increases often occur in flight for reasons which may or may not be under the control of the pilot; to obtain the best performance from the aircraft in the presence of a changing total drag figure some knowledge of the causes and effects of drag is necessary.

3. The total drag on an aircraft in flight is made up of two basic types of drag, each of which is caused by different features of the aircraft design. The basic types of drag are :—

(*a*) Profile drag.

(*b*) Induced drag.

Profile Drag

4. Profile drag can be further separated into :—

(*a*) Form drag.

(*b*) Skin friction.

5. **Form Drag.** This part of the total drag arises from the fact that when air flows past an object, a pressure is experienced which acts along the line of the airflow and in the same direction. The total pressure depends on the extent to which the object disrupts the smooth flow of the air. An example of extreme form drag is the effect of a flat plate at right angles to the airflow. Any body, however streamlined, is a source of form drag whenever relative motion occurs between it and the air.

6. **Skin Friction.**

(*a*) *The Boundary Layer.* Skin friction is caused by the resistance which is set up when relative motion exists between the surface of a body and the air; contact between the two gives rise to a layer of retarded air in immediate contact with the surface over which it is passing. This layer is known as the *boundary layer* and the amount of drag arising from it is determined by the nature and thickness of the flow in the layer. The thickness of an average boundary layer varies between about $\frac{1}{16}$ inch and $\frac{1}{4}$ inch.

(*b*) *Laminar Boundary Layer.* The amount of drag produced depends on whether the flow in the boundary layer is laminar or turbulent. Laminar flow is an orderly motion in which successive strata of air particles slide past each other in much the same way as the action of a pack of cards which is thrown along a flat surface.

(*c*) *Turbulent Boundary Layer.* In a turbulent boundary layer the laminar flow gives way to a multitude of tiny vortices and eddies in which there is no set pattern of flow. When this happens, the thickness of the boundary layer increases. It is apparent that this type of boundary layer causes more drag than one that is laminar.

(*d*) The amount of skin friction depends largely on the smoothness of the surface over which the air is flowing. The more polished and the smoother the surface, the thinner the boundary layer and the easier it is to obtain laminar flow and consequently lower drag.

(*e*) *Transition Point.* That point on the wing at which the boundary layer changes from laminar to turbulent flow is called the *transition point*. Because the increase in drag resulting from a turbulent boundary layer is considerable, care is taken to preserve laminar flow over as much of the wing as possible. Skin friction is a major source of drag at high speeds and it is one of the most difficult to reduce. It can never be eliminated completely.

(*f*) The boundary layer and its behaviour under different conditions of airflow has a profound and fundamental effect on the flight of an aircraft. For this reason a more detailed approach is made to the subject in Chapter 5, "Stalling".

7. Factors Affecting the Profile Drag. The amount of profile drag of any object is determined by the following factors :—

(*a*) *Indicated Air Speed.* The profile drag of a streamlined object held in a fixed position relative to the airflow increases approximately as the square of the indicated air speed. Thus, doubling the I.A.S. increases the drag four times, and trebling the I.A.S. increases the drag nine times. This relationship, however, holds good only at comparatively low subsonic speeds. At some higher air speed, the rate at which the profile drag has been increasing with speed, suddenly begins to increase more rapidly. This characteristic is covered more fully in para. 20.

(*b*) *Shape.*

(i) When an object is placed into a moving airflow, the direction of the airflow changes to pass around the object. The more smoothly this change is accomplished the lower the drag. If the object is so shaped that it causes the airflow to become turbulent, and the smooth flow gives way to vortices and eddies, then the drag is high and there is a large difference in pressure between the front and rear of the object.

(ii) The effect of shaping or streamlining an object of given cross-sectional area is shown in the sequence of Fig. 1. The flat plate produces most drag, the cylinder about 50 per cent. of this figure, and the streamlined shape only 5 per cent.

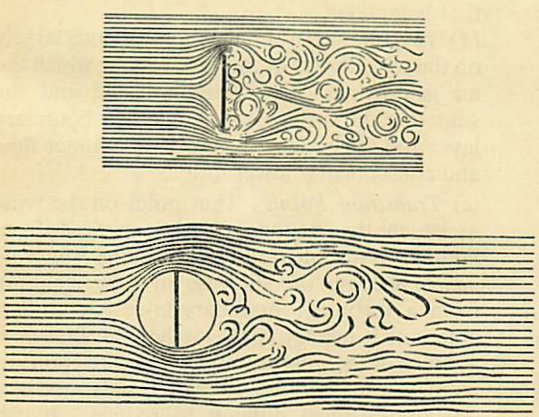

Fig. 1. Comparison of Drag

(iii) The ratio of length to breadth of any streamlined body is known as the fineness ratio (Fig. 2). For low subsonic speeds the fineness ratio is generally about 4 : 1 but at higher speeds this must be increased if the drag is to be kept as low as possible. Notice that the ratio can be increased by either increasing the length or decreasing the breadth ; for example, for a given cross-sectional area the fineness ratio can be made larger by increasing the length.

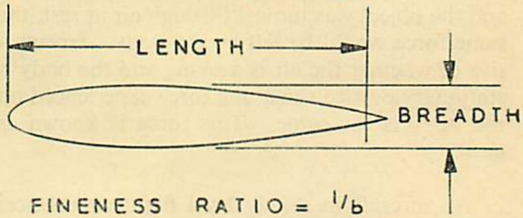

Fig. 2. Fineness Ratio

(*c*) *Interference Drag.* When conflicting airflows meet at the point where one component of the aircraft is attached to another, interference drag is caused. The effect of this interaction can be reduced by fairing the components into each other by the use of suitably shaped fillets.

(*d*) *Surface Smoothness.* As stated in para. 6(*d*) the magnitude of the skin friction drag is determined to a great extent by the smoothness of the surface. For this reason, carefully finished surfaces are a requirement on all high-speed aircraft. A typical figure is for surface irregularities not to exceed ·0005 inch, with a wave allowance of ·0001 inch in every two inches. Constant care is necessary to preserve this finish, as the slightest irregularity, such as the remains of insects which have struck the wing at low altitudes or scratches due to careless handling, causes the local transition point to move forward to these positions. Skin friction, once almost negligible in comparison with the high form drag of earlier aircraft, has assumed increased importance with the low form drags now realized. Skin friction forms an appreciable proportion of the total drag, and on some high-performance aircraft forms as much as 35 per cent. of the total drag at high speeds.

(*e*) *Surface Area.* On high-speed aircraft the increase in form drag with size is less important than the rise in skin friction which results from the larger expanse of area (wetted area) which is in contact with the airflow. In such cases a smooth surface is essential if the benefits of low form drag are not to be neutralized by high skin friction.

Induced Drag

8. The detailed aerodynamic causes of induced drag are given in later chapters. The following is a broad physical explanation of the cause of induced drag.

9. It is an established physical fact that no system which does work, in the mechanical sense, can be 100 per cent. efficient. This means that, whatever the nature of the system, the required work is obtained at the expense of a certain loss. The more efficient the system, the smaller the ensuing loss.

10. In level flight the aerodynamic properties of the wing produce a required lift, but, as stated in the previous paragraph, this can be obtained only at the expense of a certain penalty. The name given to this penalty is *induced drag*. Induced drag is inherent whenever a wing is producing lift and, in fact, this type of drag is inseparable from the production of lift.

11. Briefly, the wing produces the lift force by making use of the energy of the free air stream. When the speed of the free air stream (and hence its energy) is low, the wing must work hardest to "absorb" sufficient energy to produce the lift; consequently under these conditions the amount of induced drag is highest. Therefore the induced drag is greatest at lower speeds and becomes less as the speed increases. More precisely, for an aircraft in level flight, induced drag varies inversely as the square of the I.A.S.

12. **Factors Affecting Induced Drag.** It has been stated that the lower the air speed the greater the induced drag, the amount of which varies inversely as the square of the I.A.S. The principal factor affecting the amount of induced drag is the plan form of the wing. Briefly, it can be said that under a given set of conditions and for a given wing span, the greater the wing area the greater the induced drag. A detailed approach to this matter is made in Chapter 6, "Wing Plan Forms".

Total Drag

13. **Variation of Drag with Speed.** The foregoing paragraphs on profile and induced drag state that in level flight the profile drag increases roughly as the square of the I.A.S., and the induced drag decreases in inverse proportion to the square of the I.A.S. The total drag of the aircraft at any moment consists, therefore, partly of profile and partly of induced drag. Fig. 3 shows how the two drags vary with speed and includes a graph of total drag, determined by adding the values of the component drags at each speed.

14. **Speed for Minimum Total Drag.** In Fig. 3 it can be seen that the indicated speed for minimum total drag occurs at the point where the induced and profile drags are equal, and not at the lowest possible speed. This is an important speed in the economical operation of the aircraft and further references to it are made in Vol. 2, Part 3 (Range and Endurance).

15. **Drag and Speed.** As the drag in level flight must be balanced by the thrust, and as the thrust is limited by the power available from the engine, it is necessary, in order to obtain the maximum performance, that the total drag must be kept to a minimum. If an aircraft is accelerated in level flight, commencing from the lowest possible speed, with the engine giving the maximum thrust, the acceleration continues until the speed has risen to a figure at which the total drag equals the thrust from the engine; if the drag can then be decreased by some means the aircraft begins to accelerate again to some higher speed until the drag once more reaches the same figure as the thrust.

Coefficient of Drag

16. **Drag of a Flat Plate.** It has been shown in Chapter 2 that when moving air is brought to rest in a tube facing into the airflow the pressure exerted is given by the expression:

$$\text{Total pressure} = \tfrac{1}{2}\rho V^2 S$$

where S is the area of the tube. When a flat plate is placed at right angles to the airflow the air particles are not trapped, as they are in the tube; instead, they spill around the edges, causing strong turbulence at the rear of the plate and a

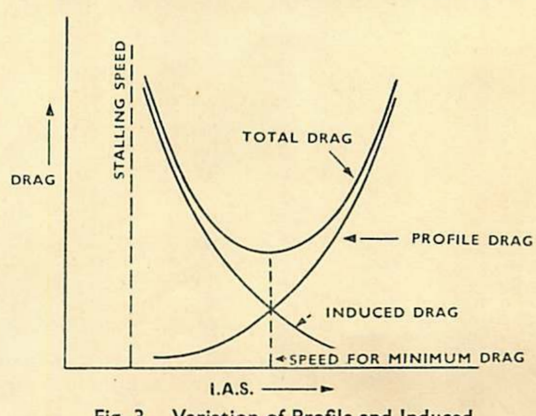

Fig. 3. Variation of Profile and Induced Drag with Speed

complete disruption of the streamline flow. The dynamic pressure on the front of the plate causes a certain increase in pressure and so a certain drag, while the action of the turbulence at the rear is to cause decreased pressure, or what is loosely termed a suction. For these reasons the actual force on a flat plate is slightly greater than that indicated by theory and can be shown to be 1·28 times the theoretical value. Therefore for a flat plate :

$$\text{Drag} = 1{\cdot}28\ \tfrac{1}{2}\rho V^2 S$$

The figure 1·28 is known as the drag coefficient (C_D) of a flat plate. It is, in fact, a correction factor that is applied to the theoretical drag given by the $\frac{1}{2}\rho V^2 S$ term.

Drag of Streamlined Shapes

17. When a number of streamlined objects of the *same cross-sectional area(s)*, but of different aerodynamic shapes and fineness ratios, are compared in a given air stream it is found that each body has a total drag different from the others. The total drag depends on the efficiency of the streamlining or the amount of disturbance produced in the smooth airflow.

18. **Low Coefficients of Drag.** Since each body has the same cross-sectional area the theoretical drag in each case is the same. The variations in the measured drags can be attributed to the different drag coefficient of each body. On objects that are efficiently streamlined the drag coefficient may be as low as ·008. When the theoretical drag is multiplied by this low figure the actual resistance is found to be very low in comparison.

Variation in C_D

19. **Variation in C_D at Constant Speed.** The drag coefficient of each body is constant only while the body retains the same attitude in relation to the airflow ; a change of attitude away from that which gives the lowest drag causes an immediate rise in the C_D. This is a natural effect, as in the displaced attitude the cross-sectional area is increased and the contours of the external lines are altered, thus producing not only a greater dynamic pressure but also greater turbulence and so a greater pressure difference acting along the line of movement of the air stream.

20. **Variation in C_D with Increasing Speed.** If a body with a known C_D is placed in an air stream of subsonic speed a certain total drag is produced. If the speed of the air stream is steadily increased the drag increases as the square of the I.A.S., and at a given speed the amount of drag can be calculated from the usual drag formula. At some fairly high subsonic speed, however, the drag suddenly begins to increase at a greater rate than that calculated from the drag formula. This sudden rise in the rate of increase is caused by effects arising from the compressible nature of the air. These effects, negligible at low speeds, fundamentally modify the nature of the airflow around the body, and in order to calculate the drag under these conditions *the drag coefficient must be raised to account for compressibility effects.* The variation of C_D in the presence of compressibility is dealt with in Chapter 14, "Transonic and Supersonic Aerodynamics".