PART 1 : SECTION 5

CHAPTER 1

AIRFRAME DESIGN AND RIGIDITY

Introduction

1. Section 1 explains the principles of flight without regard to the strength or method of construction of the aircraft ; this chapter is devoted mainly to a brief study of airframes from the designer's viewpoint. It contains short descriptions of the construction of the airframe and the materials used.

2. This chapter outlines some of the general problems confronting the aircraft designer and the procedure required to obtain a new type of aircraft for the Service. Flutter and its cause are covered in the second part of the chapter under the heading "Rigidity".

3. **Definitions.** To avoid misconceptions of the engineering terms used in this chapter the following list of definitions is included :—

Tensile Load.	One tending to stretch the member.
Bending Load.	One tending to bend the member.
Compressive Load.	One tending to shorten the member.
Shear Load.	One which tends to cause the sliding of one part of the member over another.
Stress.	The force exerted between two contacting bodies or parts of a body. It is measured as the load per unit area.
Strain.	The deformation caused by stress. It is recorded as the change of size over the original size.
Elastic Limit.	When stress exceeds the elastic limit of a material, the material takes up a permanent "set", and on release of the load it will not return completely to its original shape.
Stiffness or Rigidity.	The ratio of stress over strain.
Ultimate Strength.	That point beyond which, if stress is increased, the material will fail.

Designing a New Aircraft

4. When the Air Staff decide that a new type of aircraft is needed, a specification is prepared stating the required performance in terms of speed, range, ceiling, armament, load to be carried, etc., and the appropriate emphasis placed on each. For example, the all-important requirement for a new interceptor may well be quick take-off and climb to a stated height. The external conditions in which the aircraft is required to operate must also be stated, because the ability to operate in all parts of the world is needed in most, but not all, Service aircraft. The strength and length of runways that will be available must be taken into account so that aircraft and runways progress in phase. General design requirements common to many or all aircraft are not included in this specification, as these are available in A.P.970, "Design Requirements for Aircraft".

5. The specification must also give the strength requirements. If these are made too severe, the aircraft will be penalized by excessive structure weight ; if not severe enough, there is a risk of failures leading to accidents and/or maintenance difficulties. In choosing these strength conditions, the aim must be to ensure that the aircraft will be able to carry out safely all the normal manœuvres appropriate to its role. It is desirable to make the aircraft as strong as possible, but the extra structural weight needed to ensure adequate strength for certain manœuvres must not be out of proportion to the advantage gained. Manœuvres for which aircraft are not stressed are called prohibited manœuvres, *e.g.* the bunt and flick roll.

6. The specification therefore includes the maximum acceleration (*i.e.* g loads) to be allowed for in flight. It also stipulates a factor of safety to allow for unforeseen contingencies or accidental exceeding of the limits specified. This factor is usually 1·5. Small variations in manufacture may result in the ultimate strengths of similar aircraft varying by as much as 20 per cent., but the designer must ensure that the weakest has the required factor of safety.

7. Pilots must never use the existence of these factors of safety as an excuse for exceeding the

flying limitations specified in Pilots' Notes, because these factors are based on the ultimate strength of the material and not on the elastic limit. Although small excesses probably will not cause the aircraft to break up in the air, it will be distorted and weakened to such an extent that it may fail on a subsequent flight unless careful inspection discovers the wrinkled panels and loosened rivets.

8. It is usual for specifications to be sent to several firms for study. The design team of each firm then decides the form and size of aircraft to meet these requirements, selects suitable engines, and estimates as closely as possible the weight, performance, and range of their proposed design. The best designs are then selected on a competitive basis for development.

9. The requirements for speed and range are usually so severe that only an aerodynamically clean monoplane design can be used, and design effort is concentrated on achieving the minimum drag by careful positioning of wings, fuselage, tail unit, and engines, and by the cleanest possible stowage of radar aerials, armament, etc. Still further reductions in drag are possible by eliminating the tail unit, and even the fuselage, by using a flying wing design ; but the problems of longitudinal control and stability are then difficult to solve satisfactorily. In every heavy or high-speed design, much care must be taken to provide controls which require a minimum of force to operate them and which are effective throughout the speed range.

10. If short landing and take-off distances are the primary requirement, the designer has a wider choice of layouts, and can save weight by using a fixed undercarriage and external bracing struts if he considers them advantageous.

11. After the layout has been decided, work starts in the wind tunnel on models of the selected designs to check the exact outline of the aircraft, the lift and drag, to work out maximum air loads that will be exerted on all surfaces under all possible conditions of flight, the flight characteristics, and the control-surface loads involved. During this stage, a full-size wooden mock-up is made and positions found for models of all the equipment to be carried in it. This mock-up is also used to check the field of view provided for the aircrew, and to ensure that sufficient space is available for the air and ground crews to work on the equipment efficiently.

12. The detailed design of the airframe structure is then begun. The airframe must provide :—

(*a*) A smooth skin of the required aerodynamic form.

(*b*) Sufficient strength to withstand aerodynamic, landing, and handling loads. The aerodynamic loads are calculated from the wind tunnel experiments for the accelerations and speeds in the Air Staff specification and multiplied by the factor of safety. Landing loads are given in A.P.970 to cover heavy landings, cross winds, etc. Loads imposed by manhandling on the ground, especially on light aircraft, are often many times greater than the aerodynamic loads and must be allowed for if the aircraft is not to be covered with "Do not push here" and "No step" signs.

(*c*) Sufficient stiffness to retain its correct shape under aerodynamic loads (see paras. 14 to 20).

(*d*) Mounting points for the engines, armament, fuel tanks, equipment, etc.

(*e*) Protection, often in a pressurized compartment, for aircrew and radio gear ; warmth for crew and armament ; and cooling for engines and electrical gear.

(*f*) Suitable breakdown points, to enable the aircraft to be dismantled for transport or repair by replacement of components.

(*g*) The minimum number of points requiring examination and lubrication by servicing crews, and easy access to them.

The design should lend itself to easy and cheap production methods and easy repairs. With aircraft speeds constantly rising, necessitating a complex structure to provide the strength, this requirement is becoming more difficult to meet.

13. When the general arrangement of the aircraft is settled, the structural design may proceed. In this the designer has complete freedom of choice, but he is usually influenced by past practice and experience and the ever-growing importance of adequate structural rigidity, which is just as vital as adequate strength. Some effects of inadequate rigidity which can cause structural failure are discussed under the next heading.

RIGIDITY

Aileron Reversal

14. To raise one wing, the aileron attached to

that wing is lowered (Fig. 1). This increases the lift of the aileron (A_2), exerting an upward force on the hinge. If the wing has insufficient stiffness it will twist about its torsional axis, raising the trailing edge relative to the leading edge, thus reducing the incidence of the wing. This in turn decreases the lift of the wing (L_3), and in particularly bad cases may exceed the lifting effect of the aileron (*i.e.* $L_3 + A_3$ becomes less than $L_1 + A_1$). As a result the wing goes down—the opposite effect to that intended. This is known as aileron reversal.

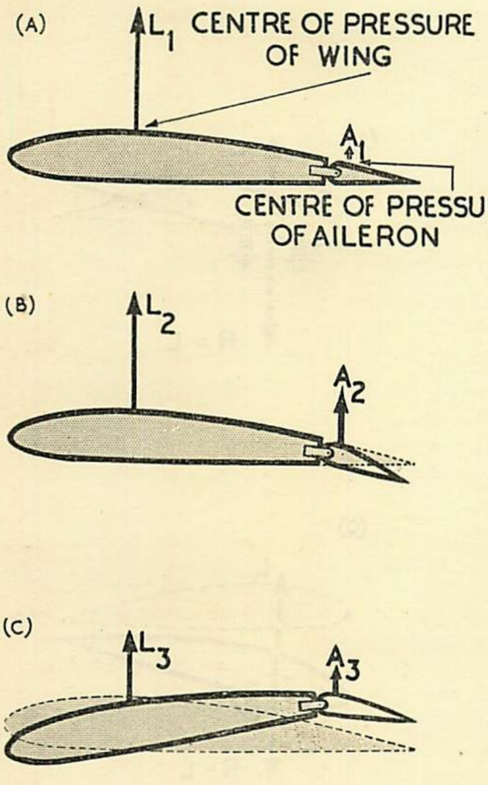

Fig. 1. Aileron Reversal

Divergence (See Fig. 2.)

15. In extreme cases, lack of torsional rigidity in the wing causes divergence. If the incidence of a wing is momentarily increased, the lift of the wing will also increase, and the centre of pressure will move forward. Should the elastic axis (torsional axis) of the wing (a line roughly parallel to the spar, on one side of which the wing rises and on the other side falls as it is twisted) be behind the centre of pressure, both the increase of lift and its forward movement magnify the couple which is twisting the wing in the direction of increased incidence. Conversely, should the initial disturbance decrease the angle of incidence, the decreased lift and the aft movement of the centre of pressure behind the elastic axis tend further to reduce the incidence. In both cases this twisting action is opposed by the torsional reaction of the wing (torsional stiffness × α, where α is the angle through which the wing has been twisted); but since the lift force increases with the square of the speed, there is a critical speed (known as the divergent speed) beyond which the aerodynamic couple will build up more rapidly with the change of incidence than the torsional reaction of the wing, and consequently the wing will continue to twist until it breaks off. This is avoided in either of two ways: by making the wing sufficiently stiff in torsion (but not necessarily in bending) so that the divergent speed is well beyond the maximum permissible speed for the aircraft; or by designing the wing so that its elastic axis is in front of the aerodynamic axis, in which case divergence cannot occur at any speed (Fig. 2c).

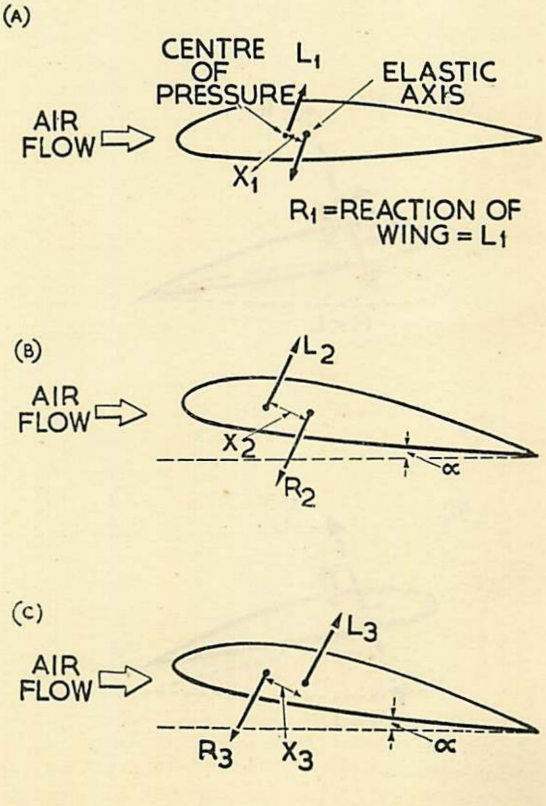

Fig. 2. Divergence

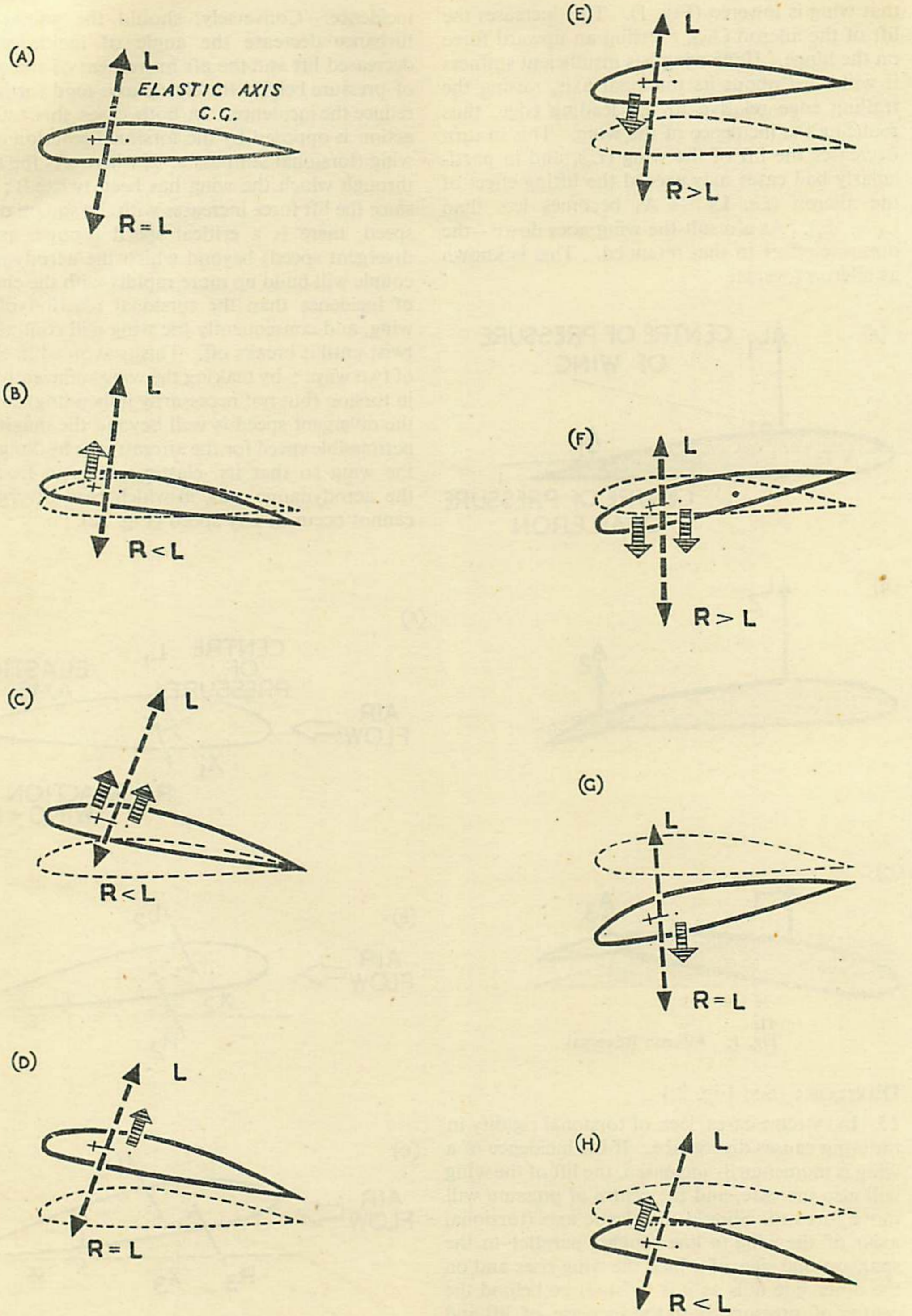

Fig. 3. Torsional Flexural Flutter

Flutter

16. Flutter is another possible cause of structural failure. This is a violent vibration of the aerofoil surfaces caused by interaction of their mass and aerodynamic loads. Three forms of flutter affect the wing :—

(*a*) Torsional flexural flutter.

(*b*) Torsional aileron flutter.

(*c*) Flexural aileron flutter.

17. **Torsional Flexural Flutter.** Torsional flexural flutter is akin to divergence and occurs at a critical speed determined by the rigidity of the wing. It can be prevented either by complete mass balancing of the wing (expressed simply but slightly inaccurately, this means getting the C. of G. on the elastic axis) if it is practicable, or by increasing the stiffness of the wing until the critical flutter speed is well beyond the maximum permissible speed for the aircraft. The cycle of events will be evident from the diagram in Fig. 3. The black arrows show the direction and magnitude of forces. The grey arrows show the direction and rate of motion. The original position of the wing is shown in dotted outline.

(*a*) The wing is in stable horizontal flight. The lift is balanced by the downward reaction force produced by bending of the wing due to the weight of the aircraft.

(*b*) The incidence of the wing is momentarily increased, causing increased lift. The lift is now greater than the reaction, and the wing starts to bend upwards.

(*c*) Inertia causes the C. of G. of the wing to lag behind the movement of the elastic axis. If the C. of G. is behind the elastic axis a further increase of incidence occurs, with a corresponding further increase in lift.

(*d*) Stiffness of the wing brings the elastic axis to rest. Inertia of the wing mass causes the C. of G. to rise further, reducing the angle of incidence.

(*e*) As wing incidence decreases, lift L becomes less than the reaction R, so the wing starts to descend.

(*f*) The wing is descending, the rate of travel of the elastic axis and the C. of G. being the same.

(*g*) Wing stiffness halts the downward travel of the elastic axis ; the inertia of the wing mass through the C. of G. now exerts a twisting movement to increase the angle of incidence.

(*h*) Lift L again exceeds the reaction force R, and the flutter cycle starts again.

18. **Torsional Aileron Flutter.** The diagrams in Fig. 4 show the first half-cycle of torsional aileron flutter. From these it will be seen that there are a

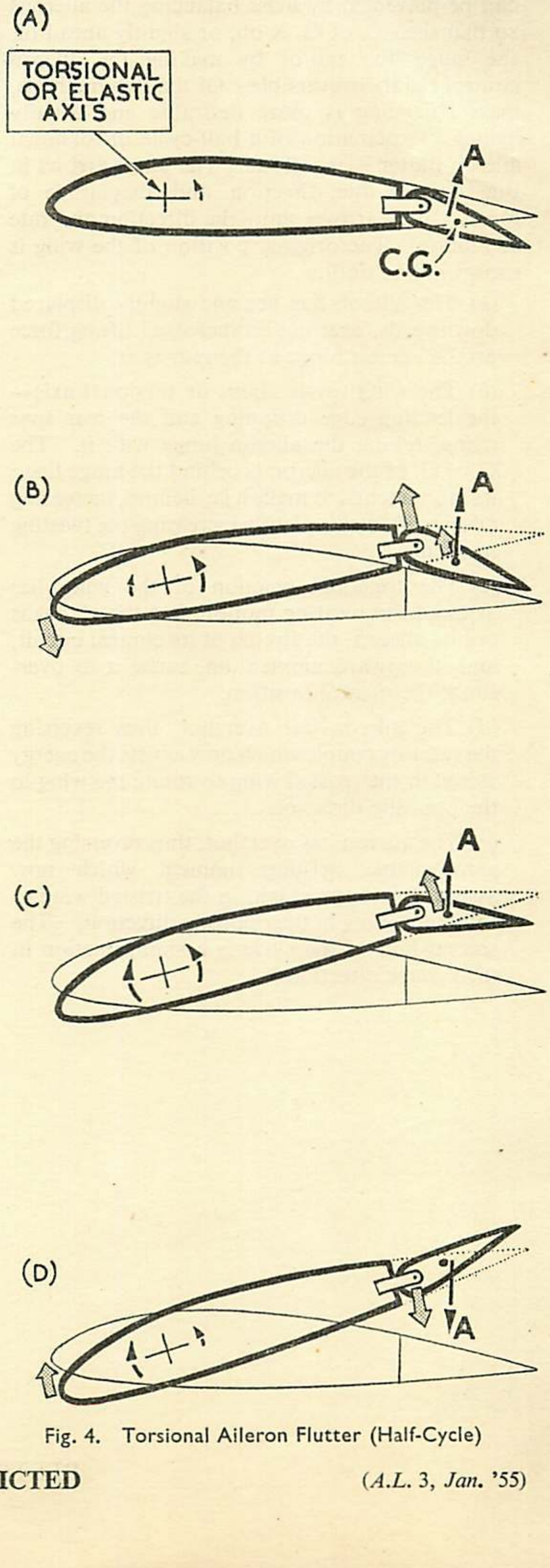

Fig. 4. Torsional Aileron Flutter (Half-Cycle)

number of features in common with aileron reversal, and it should be easy to see how the forces are developed. Torsional aileron flutter can be prevented by mass balancing the ailerons so that their C. of G. is on, or slightly ahead of, the hinge line and/or by making the aileron control rigidly irreversible. Of the two methods, mass balancing is more desirable and usually lighter. Explanation of a half-cycle of torsional aileron flutter is as follows. The black arrows in Fig. 4 show the direction and magnitude of forces ; grey arrows show the direction and rate of motion. The original position of the wing is shown in fine outline.

(*a*) The aileron has become slightly displaced downwards, exerting an increased lifting force on the aileron hinge at the rear spar.

(*b*) The wing twists about its torsional axis—the leading edge dropping and the rear spar rising, taking the aileron hinge with it. The C. of G. of the aileron is behind the hinge line ; its inertia tends to make it lag behind, increasing aileron lift, consequently increasing the twisting moment.

(*c*) The torsional reaction of the wing has arrested the twisting motion, but the air loads on the aileron, the stretch of its control circuit, and its upward momentum, cause it to overshoot the neutral position.

(*d*) The aileron has overshot, thus reversing the twisting couple which now assists the energy stored in the twisted wing to rotate the wing in the opposite direction.

(*e*) The aileron has overshot, thus reversing the aerodynamic twisting moment which now assists the energy stored in the twisted wing to rotate the wing in the opposite direction. (The second half of the cycle is a similar action in the reverse direction.)

19. **Flexural Aileron Flutter.** Flexural aileron flutter (Fig. 5) is generally similar to torsional aileron flutter, but is caused by the movement of the aileron lagging behind the rise and fall of the outer portion of the wing as it flexes, thus tending to increase the oscillation. This type of flutter is prevented by mass-balancing the aileron. The positioning of the mass balance weight is important—the nearer the wing tip the smaller the weight required. On many aircraft the weight is distributed along the whole length of the aileron in the form of a leading edge spar, thus increasing the stiffness of the aileron and preventing a concentrated weight starting torsional vibrations in the aileron itself.

20. So far only wing flutter has been discussed, but a few moments' consideration will show that mass-balancing must be applied to elevators and rudders to prevent their inertia and the springiness of the fuselage starting similar troubles. Mass-balancing is extremely critical ; hence, to avoid upsetting it, the painting of aircraft markings, etc., is no longer allowed on any control surface. The danger of all forms of flutter is that the extent of each successive vibration is greater than its predecessor, so that in a second or two the structure may be bent beyond its elastic limit and fail.

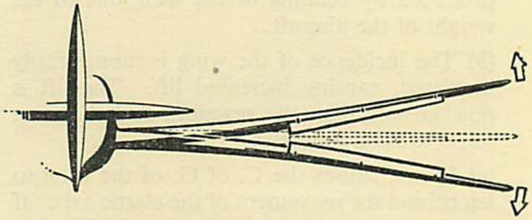

Fig. 5. Flexural Aileron Flutter