Chapter 1

INTRODUCTORY SURVEY

1·1 Aims and importance of the study of control and stability

An aircraft is a kind of vehicle and a vehicle is a kind of tool—a machine tool—for it is a mechanical appliance so designed and made that it enables men to do what they could not do with their unaided bodies. Vehicles are machine tools for transportation and each kind of vehicle is made to move and carry in a definite medium and subject to certain external constraints. For instance, a locomotive moves in the medium air and is constrained to follow a linear track while a ship moves in the twin media of water and air and is so constrained by the forces of gravity and buoyancy that its centre of gravity always lies on or near the surface separating water and air. The means for the control of vehicles vary greatly from type to type, and depend especially on such external constraints as may be present. Thus a motor car requires no control for vertical position since it is constrained to move on the surface of separation of earth and air and its track on this surface is controlled by varying the curvature of path in a suitable manner. An aircraft in flight shares with a submerged submarine the unusual condition of entire freedom from geometrical constraint and it can only be guided in its three-dimensional path by the indirect process of modifying the aerodynamic forces upon it.* Thus it is clear from the start that the control of aircraft will present problems of unusual complexity.

Another feature of aircraft in flight is that, on account of their numerous degrees of freedom and of the high speeds of flight, they are specially prone to instability unless appropriate precautions are taken, and the consequences of any but very mild instabilities will be disastrous. Hence the stability of aircraft is a subject well worthy of close study. But stability is only one aspect of the dynamical characteristics; the general

* For lighter-than-air craft we should add the forces of gravity and of buoyancy as being under control.

dynamical behaviour profoundly affects the comfort of passengers and the suitability of the aircraft for a gun or bombing platform. Therefore we must extend our inquiry to a general examination of dynamical behaviour, including the response to control movements and to gusts.

1·2 Pilots—human and automatic

Most aircraft are controlled only by human pilots and hitherto nearly all have been designed for at least occasional human control. The capacities of the human pilot are therefore the basis for the design of controls; moreover, the question of stability can only be intelligently discussed in the light of the characteristics of the pilot.

From the present point of view the most important characteristics of pilots are:

(1) Muscular strength.

(2) Reaction time.

(3) Proneness to fatigue.

(4) Sensitiveness to acceleration.

(5) Sensitiveness to changes of the force reactions on the controls.

(6) Sensitiveness to changes of position, as of the limbs, or of visible objects such as the pointers of instruments.

(7) Adaptability.

These will be discussed separately.

It is obvious that the loads on the control stick and pedals required for the effective control of the aircraft in all operational conditions must be within the physical capacity of all fit pilots; moreover the sustained loads must not be great enough to cause undue fatigue. No very precise figures for the forces can be stated, but those given in Table 1·2, 1, which are due to M. B. Morgan, will serve as useful guides. It appears from experience that forces of even a few pounds, when continually sustained, cause discomfort and fatigue. Hence it is necessary that each control should be provided with a trimming device by which the control force can be balanced out for any setting of the control. Another important aspect of control forces is their harmony; it is well recognized that pilots strongly dislike a mixture of heavy and light controls. Again no very precise criteria can be laid down but most pilots would agree

that controls are in satisfactory harmony when the maxima for the lateral stick force, fore-and-aft stick force and pedal force are in the proportion 1 : 2 : 4.

Reaction time may be defined as the time which elapses between the impact of a physical stimulus on some sense organ such as the eye or touch spot on the skin and the beginning of

TABLE 1·2, 1. MAXIMUM CONTROL FORCES EXERTED BY THE PILOT. ALL FORCES ARE IN POUNDS

Nature of force		Aileron (sideways or peripheral force)		Elevator (push or pull)		Rudder, push
		Stick	Wheel	Stick	Wheel	
Greatest effort of which pilot is capable in emergency for a very short time		90 (two hands)	120 (two hands)	180 (two hands)	220 (two hands)	400
Maximum force which it is permissible to demand of the pilot, even in an emergency, for a short time	Two hands	—	80	100	110	200
	One hand	50	50	70	70	
Maximum force which the pilot cares to exert for a short time	Two hands	—	30	—	40	60
	One hand	20	20	30	30	

Where blanks occur it is intended to convey that the use of two hands should not be demanded.

The maximum tolerable forces are reduced when the cockpit is cramped.

the responsive movement of hand or foot. Reaction time varies somewhat from individual to individual and depends on attention, practice, the nature of the task and of the stimulus and, most importantly, the physical state of the subject. It is reduced by attention and practice and increased by fatigue but particularly by oxygen starvation (anoxia). Visual reactions are appreciably slower than tactual, the additional lag being probably associated with the photochemical reaction in the retina. The normal reaction time to touch and to sound is about 0·12 second while it is about 0·17 second for a visual stimulus; these figures refer to determinations in the laboratory under favourable conditions.

Reaction time is important in relation to the steadiness of flight which the pilot is able to maintain, particularly in bumpy air, and it influences the amount of instability of the aircraft which can be tolerated. It is recognized that an aircraft may behave quite satisfactorily in the hands of an experienced pilot when it is subject to one or more instabilities, provided that these are not too severe. One important variable is the ratio of the time required to double the amplitude of the disturbance to the reaction time of the pilot, although the magnitude of the disturbance is also of great importance. When this ratio is of the order of 50 or greater the instability will probably not be dangerous. The foregoing criterion is intended to apply only to aperiodic movements and to periodic movements of low frequency. When the frequency is greater than about $\frac{1}{2}$ cycle per second even the slightest instability will probably be uncontrollable.

Fatigue of the pilot may be of two extreme types, although in practice the effect will often be mixed. The first is physical fatigue caused by the prolonged application of control forces which are too great for comfort and the second is mental fatigue caused by the effort of attention needed to overcome the departures of the aircraft from the desired attitude, etc. Fatigue of the first kind can be minimized by designing the controls so that excessive control forces are avoided; that of the second kind will not be unduly severe provided the controls are not too sensitive and that the aircraft itself has the right dynamical characteristics.

The pilot's sensitiveness to acceleration must be considered from two aspects. First, there is the maximum acceleration which he can withstand without 'blackout' or unconsciousness, for it is clearly without profit to design the aircraft for accelerations which would cause these disabilities. A pilot is most sensitive to acceleration directed along the major axis of his body, while maximum accelerations of the aircraft in the fore-and-aft and lateral directions are much smaller than in the 'normal' direction. Hence large normal accelerations are better tolerated when the pilot is prone than when he sits vertically; the maximum tolerable acceleration can also be increased by the use of 'anti-g' suits. In the design of large aircraft the accelerations which can occur at parts far distant from the

centre of gravity during angular motions must be considered (see § 3·3). Angular accelerations unaccompanied by linear accelerations, such as may occur in the vicinity of the C.G. in the rapid initiation of a roll, do not appear to be physiologically important. Second, the pilot's sensitiveness to *small* accelerations may be of value to him as an aid to maintaining steady flight.

The pilot's sensitiveness to changes of control force and of control position are of importance in helping him to maintain steady flight, but the sensitiveness to changes of force seems to be the more important.

An adaptable pilot is one who quickly becomes accustomed to and masters a new aircraft or a new system of control. All human beings, fortunately, have a tendency to like what they have become accustomed to, even when the familiar thing is very faulty, but this is accompanied by a more or less pronounced and irrational dislike of change. The bearing of this on the design of controls is that almost any innovation will be disliked at first by a large proportion of pilots, but this dislike will be removed by education and experience if the innovation is intrinsically good.

The most important fact about automatic pilots is that the aircraft and its automatic pilot form a *single dynamical system* and the mechanism and gearing of the pilot must be so adapted to the aircraft that the whole system has satisfactory characteristics. One obvious requirement is that the system shall be definitely stable in all circumstances. It is, however, incorrect to suppose that the automatic pilot which makes a given aircraft the most stable is therefore the best. The fact is that stability is concerned with the *ultimate* consequence of a disturbance and stability, in the technical sense of the word, is high when the motion induced by a disturbance ultimately decays rapidly. But this condition may be compatible with a large amplification of the disturbance in the *early* stages of the induced motion, which is clearly most undesirable. Hence an automatic pilot must be designed to give the greatest steadiness or *stabilization* at all stages of the induced motion. The optimum arrangement will be one for which the *stability* is good, but usually not at an absolute maximum.

We cannot enter here into the technicalities and theory of automatic control (see §§ 15·2 and 15·3), but the importance of

avoiding lag in the mechanism must be emphasized. Lag in an automatic pilot corresponds with reaction time in a human pilot and is similarly detrimental; special devices have been invented for its effective neutralization.

1·3 The dynamical basis for the study of stability and control

All aircraft are deformable—that is, the relative positions of *all* their parts vary somewhat with the loads applied in flight. However, it has been customary to ignore the deformations of the main structure in discussing the theory of stability and control and only to take account of them in special inquiries concerning such matters as flutter and reversal of control. This simplification, though never exact, is often justified and may be accepted as necessary in the first approach to the subject, since the theory is vastly complicated when the deformations of the structure are allowed for. Hence we begin by assuming that the main aircraft structure and each individual control surface is a rigid body, but we are forced to abandon this assumption when the speed of flight is high in relation to the stiffnesses of the structure.

The dynamically dominant feature of the whole problem is that the aircraft moves in the gravitational field of the earth. The value of the apparent acceleration due to gravity varies slightly with latitude and with altitude, but the variations are negligible. Exceptionally, the variation of g with altitude would become appreciable for trans-atmospheric craft.

1·4 The aerodynamic basis

Most of the current theory of control and stability is based on very elementary aerodynamic theory helped by the results of ad hoc aerodynamic experiments which are not yet fully explained by fundamental aerodynamic theory. In many instances the aerodynamic data do not go beyond the ordinary non-dimensional coefficients C_L, C_D, etc., appropriate to the aerofoils concerned. Such coefficients are never strictly applicable to motions in which the angles of incidence of the various surfaces vary with time, but usually the error involved here is small. However, more serious errors arise where the aerodynamic forces or moments deviate importantly from being

linear functions of incidence or of control angle, as is assumed in all elementary treatments of aircraft dynamics. It is notorious that the graphs of hinge moment against control angle for certain controls, e.g. Frise ailerons, are far from straight; a curve with a point of inflexion in the neutral region is quite usual.

The non-dimensional coefficients such as C_L for an aerofoil or body of given shape set at a given attitude are functions of the non-dimensional parameters R and $\mathbf{M}$. Here R is the Reynolds number given by

$$R = \frac{Vl}{\nu}, \tag{1·4, 1}$$

with V = velocity of flight,
l = a typical linear dimension such as mean wing chord
and ν = kinematic viscosity of the air
$= \mu/\rho$, (1·4, 2)
where μ = viscosity of the air
and ρ = air density.

The Mach number $\mathbf{M}$ is the ratio of the speed of flight to the speed of sound in the undisturbed air; thus

$$\mathbf{M} = \frac{V}{a}, \tag{1·4, 3}$$

where a is the velocity of sound in the surrounding atmosphere. The Mach number is a very convenient parameter for indicating the importance of the compressibility of the air in the circumstances of the flight considered. When $\mathbf{M}$ is less than about 0·3 the influence of compressibility is usually negligible and for thin aerofoils at small incidences the effect is slight for Mach numbers up to about 0·7.

The Reynolds number serves to indicate in a broad way the relative importance of the forces of fluid friction and of inertia within the fluid; the lower the value of R the more relatively important is the fluid friction. Variation of a non-dimensional aerodynamic coefficient, such as C_L for a given aerofoil at a given angle of incidence, with R is usually called *scale effect*. Even for values of R in excess of several millions, scale effect may not be negligible. This may be associated with chordwise shift of the region of transition from laminar to turbulent

motion in the boundary layer as R varies and to surface roughnesses penetrating beyond the laminar sub-layer at high values of R. An apparent scale effect, especially in wind tunnel tests, may be associated with increasing turbulence in the air stream as the speed rises. In as much as transition region and surface roughness may vary largely from aircraft to aircraft of the same type, and with time for a given aircraft, it must be expected that the full-scale aerodynamic coefficients will exhibit corresponding variations.

An interesting interpretation of the Reynolds number for motion in a gas is provided by the following formula

$$R = k\mathbf{M}\left(\frac{l}{\lambda}\right), \qquad (1\cdot4,\ 4)$$

where k is a numerical constant which depends slightly on the nature of the gas and differs little from unity, $\mathbf{M}$ and l have their former meanings, and λ is the mean free path of the molecules of the gas. We see, therefore, that in place of taking $\mathbf{M}$ and R as fundamental parameters we may use $\mathbf{M}$ and (l/λ).* This has the advantage of being applicable when the conception of viscosity no longer has meaning, as when the mean free path is comparable with the linear dimensions of the body. In such circumstances it might be appropriate to substitute for $\mathbf{M}$ the ratio V/C, where C is the root mean square velocity of the molecules of the gas, for C and a are proportional for a given gas.

1·5 Methods of control

We have already remarked in § 1·1 that the path of an aircraft is controlled by varying the aerodynamic forces upon it. This can be done in two main ways:

(*a*) By varying the propulsive force, provided by an airscrew or jet, in magnitude or direction.

(*b*) By changing the relative positions of parts of the aircraft.

Method (*a*) is used chiefly in controlling the inclination to the horizontal of a rectilinear flight path but it has already been used for directional control in helicopters. In method (*b*) a change of configuration is so arranged that a local change of aerodynamic force occurs, giving rise to a moment about the centre of gravity of the aircraft. The aircraft then rotates and,

* λ/l is known as the Knudsen number.

in general, alters its attitude to the flight path with the consequence that the aerodynamic forces are further modified. The local change of configuration may be secured by distortion of the structure, as with wing warping which was used for lateral control on some early aeroplanes, but usually at the present day by rotating a more or less rigid part of the structure, called a control surface, about hinges fixed in the main structure. Sometimes the relative movement is compounded of rotation and sliding, as in some landing flaps. Pure sliding might also be used.

The foregoing by no means exhausts the possibilities of control. For example, control could certainly be achieved by localized suction suitably arranged, but no such arrangement has yet been used. Spoilers, which reduce wing lift locally by spoiling the 'circulation', have been tried but not widely adopted. In emergencies helpful control forces can be produced by launching drogues or parachutes, e.g. anti-spin parachutes.

1·6 Some needs and difficulties

An outstanding difficulty in the design of non-power operated controls arises from the manner in which the hinge moments on flap controls vary with speed of flight. Apart from scale effect and the influence of compressibility, the hinge moment on a given rigid flap when deflected to a given angle varies as the square of the speed. Thus if the greatest and least speeds are say in the ratio 3 : 1 the hinge moments and control forces will be in the ratio 9 : 1. This would imply that the control was either unduly light at low speeds or unduly heavy at high speeds, although the disparity may be mitigated by the circumstance that somewhat smaller control movements usually suffice at the higher speeds. The designer is thus faced with the problem of 'defeating the V^2 law'. Again, on large aircraft the control flaps are also large and the hinge moments correspondingly great. Hence the pilot would be unable to operate them except by use of an excessively low gear ratio between control column or pedal and control flap; since some slowing of control movement may be tolerated on large aircraft on account of their slowness of response some reduction in the gear ratio may be acceptable.

The difficulties just mentioned are met or at least mitigated by providing the control flaps with some kind of aerodynamic

balance which reduces the hinge moments. The primitive and most obvious method of balancing is to set back the hinge from the nose of the flap but this is limited by the imperative need to avoid overbalance in *all* circumstances. Much ingenuity has been shown in the design of balancing arrangements and one of the most useful and effective is undoubtedly the spring tab. This has the most valuable feature that it gives the greatest effect in lightening the control just when it is most needed, i.e. it succeeds, in some measure, in overcoming the usual tendency towards excessive heaviness at high speeds without incurring excessive lightness at low speeds. It is worthy of remark here that the hinge moments on flap controls are affected by the responsive movement of the aircraft and it is possible to arrange matters so that this response effect is helpful.

1·7 Power-operated controls

One radical method of overcoming the difficulties outlined in the last section is to provide servo motors to operate the control surfaces. Here the force exerted by the pilot can be as small as desired in all circumstances. The paramount requirement of power operated controls is absolute reliability and this will usually require duplication of the servo motors and of the source of power. Obviously the main objections to the use of power are the extra weight and complication, but it is probable that it will be used increasingly in the future for large aircraft and for small aircraft which fly very fast. Two outstanding questions concern:

(*a*) The need to provide a manual control for use in emergency.

(*b*) The need to provide the pilot with 'feel' by feeding back to his control lever a small fraction of the full control load.

Neither of these questions is yet settled, but it appears probable that both of these needs will disappear as technique develops and pilots become accustomed to the new system.

1·8 The place of theory

It is beyond dispute that the observed behaviour of aircraft is so complex and puzzling that, without a well developed theory, the subject could not be treated intelligently. Theory has at least three useful functions: