CHAPTER 1

Introduction

1.1 The Subject Matter of Dynamics of Flight

This book is about the *motion* of *vehicles* that *fly* in the atmosphere. As such it belongs to the branch of engineering science called applied mechanics. The three italicized words above warrant further discussion. To begin with *fly*—the dictionary definition is not very restrictive, although it implies motion through the air, the earliest application being of course to birds. However, we also say "a stone flies" or "an arrow flies," so the notion of sustention (lift) is not necessarily implied. Even the atmospheric medium is lost in "the flight of angels." We propose as a logical scientific definition that flying be defined as motion through a fluid medium or empty space. Thus a satellite "flies" through space and a submarine "flies" through the water. Note that a dirigible in the air and a submarine in the water are the same from a mechanical standpoint—the weight in each instance is balanced by buoyancy. They are simply separated by three orders of magnitude in density. By *vehicle* is meant any flying object that is made up of an arbitrary system of deformable bodies that are somehow joined together. To illustrate with some examples: (1) A rifle bullet is the simplest kind, which can be thought of as a single ideally rigid body. (2) A jet transport is a more complicated vehicle, comprising a main elastic body (the airframe and all the parts attached to it), rotating subsystems (the jet engines), articulated subsystems (the aerodynamic controls) and fluid subsystems (fuel in tanks). (3) An astronaut attached to his orbiting spacecraft by a long flexible cable is a further complex example of this general kind of system. Note that by the above definition a vehicle does not necessarily have to carry goods or passengers, although it usually does. The logic of the definitions is simply that the underlying engineering science is common to all these examples, and the methods of formulating and solving problems concerning the motion are fundamentally the same.

As is usual with definitions, we can find examples that don't fit very well. There are special cases of motion at an interface which we may or may not include in flying—for example, ships, hydrofoil craft and air-cushion vehicles (ACV's). In this connection it is worth noting that developments of hydrofoils and ACV's are frequently associated with the Aerospace industry. The main difference between these cases, and those of "true" flight, is that the latter is essentially three-dimensional, whereas the interface vehicles mentioned (as well as cars, trains, etc.) move approximately in a two-dimensional field. The underlying principles and methods are still the same however, with certain modifications in detail being needed to treat these "surface" vehicles.

Now having defined *vehicles* and *flying*, we go on to look more carefully at what we mean by *motion*. It is convenient to subdivide it into several parts:

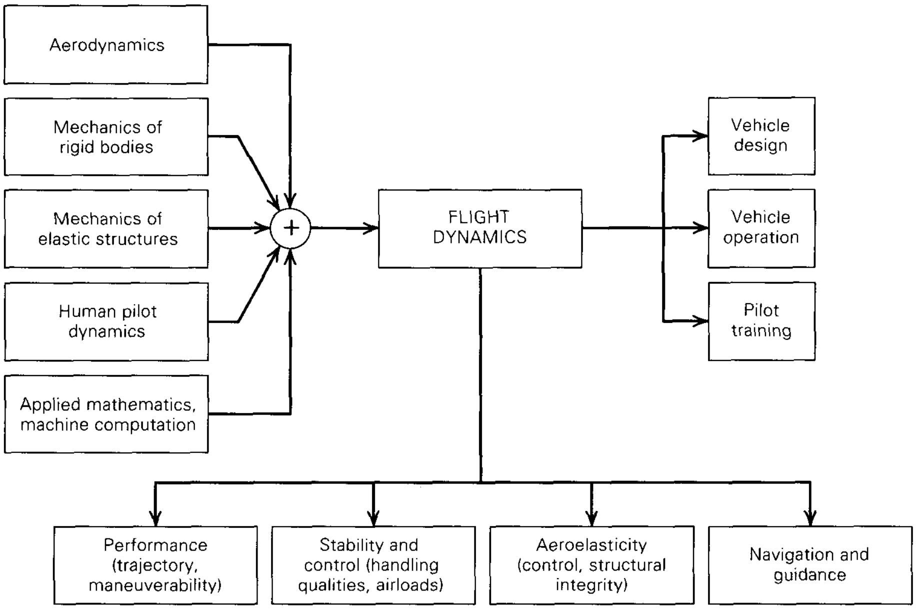


Figure 1.1 Block diagram of disciplines.

Gross Motion:

1. Trajectory of the vehicle mass center.[1]
2. "Attitude" motion, or rotations of the vehicle "as a whole."

Fine Motion:

3. Relative motion of rotating or articulated subsystems, such as engines, gyroscopes, or aerodynamic control surfaces.
4. Distortional motion of deformable structures, such as wing bending and twisting.
5. Liquid sloshing.

This subdivision is helpful both from the standpoint of the technical problems associated with the different motions, and of the formulation of their analysis. It is surely self-evident that studies of these motions must be central to the design and operation of aircraft, spacecraft, rockets, missiles, etc. To be able to formulate and solve the relevant problems, we must draw on several basic disciplines from engineering science. The relationships are shown on Fig. 1.1. It is quite evident from this figure that the practicing flight dynamicist requires intensive training in several branches of engineering science, and a broad outlook insofar as the practical ramifications of his work are concerned.

In the classes of vehicles, in the types of motions, and in the medium of flight, this book treats a very restricted set of all possible cases. It deals only with the flight

[1]It is assumed that gravity is uniform, and hence that the mass center and center of gravity (CG) are the same point.

of airplanes in the atmosphere. The general equations derived, and the methods of solution presented, are however readily modified and extended to treat many of the other situations that are embraced by the general problem.

All the *fundamental* science and mathematics needed to develop this subject existed in the literature by the time the Wright brothers flew. Newton, and other giants of the 18th and 19th centuries, such as Bernoulli, Euler, Lagrange, and Laplace, provided the building blocks in solid mechanics, fluid mechanics, and mathematics. The needed applications to aeronautics were made mostly after 1900 by workers in many countries, of whom special reference should be made to the Wright brothers, G. H. Bryan, F. W. Lanchester, J. C. Hunsaker, H. B. Glauert, B. M. Jones, and S. B. Gates. These pioneers introduced and extended the basis for analysis and experiment that underlies all modern practice.[2] This body of knowledge is well documented in several texts of that period, for example, Bairstow (1939). Concurrently, principally in the United States of America and Britain, a large body of aerodynamic data was accumulated, serving as a basis for practical design.

Newton's laws of motion provide the connection between environmental forces and resulting motion for all but relativistic and quantum-dynamical processes, including all of "ordinary" and much of celestial mechanics. What then distinguishes flight dynamics from other branches of applied mechanics? Primarily it is the special nature of the force fields with which we have to be concerned, the absence of the kinematical constraints central to machines and mechanisms, and the nature of the control systems used in flight. The external force fields may be identified as follows:

"Strong" Fields:

1. Gravity
2. Aerodynamic
3. Buoyancy

"Weak" Fields:

4. Magnetic
5. Solar radiation

We should observe that two of these fields, aerodynamic and solar radiation, produce important heat transfer to the vehicle in addition to momentum transfer (force). Sometimes we cannot separate the thermal and mechanical problems (Etkin and Hughes, 1967). Of these fields only the strong ones are of interest for atmospheric and oceanic flight, the weak fields being important only in space. It should be remarked that even in atmospheric flight the gravity force can not always be approximated as a constant vector in an inertial frame. Rotations associated with Earth curvature, and the inverse square law, become important in certain cases of high-speed and high-altitude flight (Etkin, 1972).

The prediction, measurement and representation of aerodynamic forces are the principal distinguishing features of flight dynamics. The size of this task is illustrated

[2]An excellent account of the early history is given in the 1970 von Kármán Lecture by Perkins (1970).

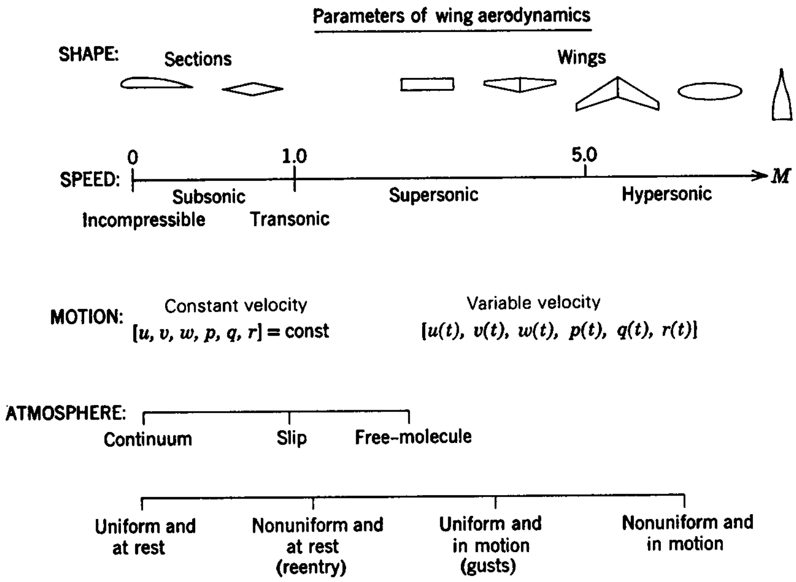


Figure 1.2 Spectrum of aerodynamic problems for wings.

by Fig. 1.2, which shows the enormous range of variables that need to be considered in connection with wings alone. To be added, of course, are the complications of propulsion systems (propellers, jets, rockets), compound geometries (wing + body + tail), and variable geometry (wing sweep, camber).

As remarked above, Newton's laws state the connection between force and motion. The commonest problem consists of finding the motion when the laws for the forces are given (all the numerical examples given in this book are of this kind). However, we must be aware of certain important variations:

1. Inverse problems of first kind—the system and the motion are given and the forces have to be calculated.
2. Inverse problems of the second kind—the forces and the motion are given and the system parameters have to be found.
3. Mixed problems—the unknowns are a mixture of variables from the force, system, and motion.

Examples of these inverse and mixed problems often turn up in research, when one is trying to deduce aerodynamic forces from the observed motion of a vehicle in flight or of a model in a wind tunnel. Another example is the deduction of harmonics of the Earth's gravity field from observed perturbations of satellite orbits. These problems are closely related to the "plant identification" or "parameter identification" problem of system theory. [Inverse problems were treated in Chap. 11 of Etkin (1959)].

TYPES OF PROBLEMS

The main types of flight dynamics problem that occur in engineering practice are:

1. Calculation of "performance" quantities, such as speed, height, range, and fuel consumption.
2. Calculation of trajectories, such as launch, reentry, orbital and landing.
3. Stability of motion.
4. Response of vehicle to control actuation and to propulsive changes.
5. Response to atmospheric turbulence, and how to control it.
6. Aeroelastic oscillations (flutter).
7. Assessment of human-pilot/machine combination (handling qualities).

It takes little imagination to appreciate that, in view of the many vehicle types that have to be dealt with, a number of subspecialties exist within the ranks of flight dynamicists, related to some extent to the above problem categories. In the context of the modern aerospace industry these problems are seldom simple or routine. On the contrary they present great challenges in analysis, computation, and experiment.

1.2 The Tools of Flight Dynamicists

The tools used by flight dynamicists to solve the design and operational problems of vehicles are of three kinds:

1. Analytical
2. Computational
3. Experimental

The analytical tools are essentially the same as those used in other branches of mechanics, that is the methods of applied mathematics. One important branch of applied mathematics is what is now known as system theory, including stability, automatic control, stochastic processes and optimization. Stability of the uncontrolled vehicle is neither a necessary nor a sufficient condition for successful controlled flight. Good airplanes have had slightly unstable modes in some part of their flight regime, and on the other hand, a completely stable vehicle may have quite unacceptable handling qualities. It is *dynamic performance* criteria that really matter, so to expend a great deal of analytical and computational effort on finding stability boundaries of nonlinear and time-varying systems may not be really worthwhile. On the other hand, the computation of stability of small disturbances from a steady state, that is, the linear eigenvalue problem that is normally part of the system study, is very useful indeed, and may well provide enough information about stability from a practical standpoint.

On the computation side, the most important fact is that the availability of machine computation has revolutionized practice in this subject over the past few decades. Problems of system performance, system design, and optimization that could not have been tackled at all in the past are now handled on a more or less routine basis.

The experimental tools of the flight dynamicist are generally unique to this field. First, there are those that are used to find the aerodynamic inputs. Wind tunnels and shock tubes that cover most of the spectrum of atmospheric flight are now available in the major aerodynamic laboratories of the world. In addition to fixed laboratory equipment, there are aeroballistic ranges for dynamic investigations, as well as rocket-boosted and gun-launched free-flight model techniques. Hand in hand with the development of these general facilities has gone that of a myriad of sensors and instruments, mainly electronic, for measuring forces, pressures, temperatures, acceleration, angular velocity, and so forth. The evolution of *computational fluid dynamics* (CFD) has sharply reduced the dependence of aerodynamicists on experiment. Many results that were formerly obtained in wind tunnel tests are now routinely provided by CFD analyses. The CFD codes themselves, of course, must be verified by comparison with experiment.

Second, we must mention the flight simulator as an experimental tool used directly by the flight dynamicist. In it he studies mainly the matching of the pilot to the machine. This is an essential step for radically new flight situations. The ability of the pilot to control the vehicle must be assured long before the prototype stage. This cannot yet be done without test, although limited progress in this direction is being made through studies of mathematical models of human pilots. Special simulators, built for most new major aircraft types, provide both efficient means for pilot training, and a research tool for studying handling qualities of vehicles and dynamics of human pilots. The development of high-fidelity simulators has made it possible to greatly reduce the time and cost of training pilots to fly new types of airplanes.

1.3 Stability, Control, and Equilibrium

It is appropriate here to define what is meant by the terms *stability* and *control.* To do so requires that we begin with the concept of equilibrium.

A body is in equilibrium when it is at rest or in uniform motion (i.e., has constant linear and angular momenta). The most familiar examples of equilibrium are the static ones; that is, bodies at rest. The equilibrium of an airplane in flight, however, is of the second kind; that is, uniform motion. Because the aerodynamic forces are dependent on the angular orientation of the airplane relative to its flight path, and because the resultant of them must exactly balance its weight, the equilibrium state is without rotation; that is, it is a motion of rectilinear translation.

Stability, or the lack of it, is a property of an equilibrium state.[3] The equilibrium is stable if, when the body is slightly disturbed in any of its degrees of freedom, it returns ultimately to its initial state. This is illustrated in Fig. 1.3*a*. The remaining sketches of Fig. 1.3 show neutral and unstable equilibrium. That in Fig. 1.3*d* is a more complex kind than that in Fig. 1.3*b* in that the ball is stable with respect to displacement in the y direction, but unstable with respect to x displacements. This has its counterpart in the airplane, which may be stable with respect to one degree of freedom and unstable with respect to another. Two kinds of instability are of interest in

[3]It is also possible to speak of the stability of a transient with prescribed initial condition.

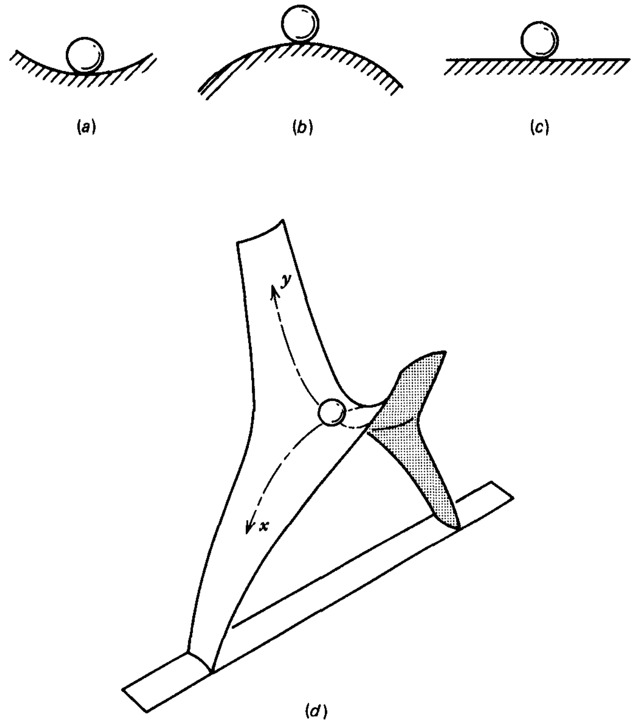


Figure 1.3 (*a*) Ball in a bowl—stable equilibrium. (*b*) Ball on a hill—unstable equilibrium. (*c*) Ball on a plane—neutral equilibrium. (*d*) Ball on a saddle surface—unstable equilibrium.

airplane dynamics. In the first, called *static instability*, the body departs continuously from its equilibrium condition. That is how the ball in Fig. 1.3*b* would behave if disturbed. The second, called *dynamic instability*, is a more complicated phenomenon in which the body oscillates about its equilibrium condition with ever-increasing amplitude.

When applying the concept of stability to airplanes, there are two classes that must be considered—*inherent stability* and *synthetic stability*. The discussion of the previous paragraph implicitly dealt with inherent stability, which is a property of the basic airframe with either fixed or free controls, that is, *control-fixed stability* or *control-free stability*. On the other hand, synthetic stability is that provided by an *automatic flight control system* (AFCS) and vanishes if the control system fails. Such automatic control systems are capable of stabilizing an inherently unstable airplane, or simply improving its stability with what is known as *stability augmentation systems* (SAS). The question of how much to rely on such systems to make an airplane flyable entails a trade-off among weight, cost, reliability, and safety. If the SAS works most of the time, and if the airplane can be controlled and landed after it has failed, albeit with diminished handling qualities, then poor inherent stability may be acceptable. Current aviation technology shows an increasing acceptance of SAS in all classes of airplanes.

If the airplane is controlled by a human pilot, some mild inherent instability can be tolerated, if it is something the pilot can control, such as a slow divergence. (Unstable bicycles have long been ridden by humans!). On the other hand, there is no margin for error when the airplane is under the control of an autopilot, for then the closed loop system *must be stable* in its response to atmospheric disturbances and to commands that come from a navigation system.

In addition to the role controls play in stabilizing an airplane, there are two others that are important. The first is to fix or to change the equilibrium condition (speed or angle of climb). An adequate control must be powerful enough to produce the whole range of equilibrium states of which the airplane is capable from a performance standpoint. The dynamics of the transition from one equilibrium state to another are of interest and are closely related to stability. The second function of the control is to produce nonequilibrium, or accelerated motions; that is, maneuvers. These may be steady states in which the forces and accelerations are constant when viewed from a reference frame fixed to the airplane (for example, a steady turn), or they may be transient states. Investigations of the transition from equilibrium to a nonequilibrium steady state, or from one maneuvering steady state to another, form part of the subject matter of airplane control. Very large aerodynamic forces may act on the airplane when it maneuvers—a knowledge of these forces is required for the proper design of the structure.

RESPONSE TO ATMOSPHERIC TURBULENCE

A topic that belongs in dynamics of flight and that is closely related to stability is the response of the airplane to wind gradients and atmospheric turbulence (Etkin, 1981). This response is important from several points of view. It has a strong bearing on the adequacy of the structure, on the safety of landing and take-off, on the acceptability of the airplane as a passenger transport, and on its accuracy as a gun or bombing platform.

1.4 The Human Pilot

Although the analysis and understanding of the dynamics of the airplane as an isolated unit is extremely important, one must be careful not to forget that for many flight situations it is the response of the total system, made up of the human pilot and the aircraft, that must be considered. It is for this reason that the designers of aircraft should apply the findings of studies into the human factors involved in order to ensure that the completed system is well suited to the pilots who must fly it.

Some of the areas of consideration include:

1. Cockpit environment; the occupants of the vehicle must be provided with oxygen, warmth, light, and so forth, to sustain them comfortably.
2. Instrument displays; instruments must be designed and positioned to provide a useful and unambiguous flow of information to the pilot.
3. Controls and switches; the control forces and control system dynamics must be acceptable to the pilot, and switches must be so positioned and designed as to prevent accidental operation. Tables 1.1 to 1.3 present some pilot data concerning control forces.
4. Pilot workload; the workload of the pilot can often be reduced through proper planning and the introduction of automatic equipment.

Table 1.1
Estimates of the Maximum Rudder Forces that Can Be Exerted for Various Positions of the Rudder Pedal (BuAer, 1954)

Rudder Pedal Position	*Distance from Back of Seat*		*Pedal Force*	
	(in)	*(cm)*	*(lb)*	*(N)*
Back	31.00	78.74	246	1,094
Neutral	34.75	88.27	424	1,886
Forward	38.50	97.79	334	1,486

Table 1.2
Hand-Operated Control Forces (From Flight Safety Foundation Human Engineering Bulletin 56-5H) (see figure in Table 1.3)

Direction of Movement		*180°*	*150°*	*120°*	*90°*	*60°*	
Pull	Rt. hand	52 (231)	56 (249)	42 (187)	37 (165)	24 (107)	
	Lft. hand	50 (222)	42 (187)	34 (151)	32 (142)	26 (116)	
Push	Rt. hand	50 (222)	42 (187)	36 (160)	36 (160)	34 (151)	
	Lft. hand	42 (187)	30 (133)	26 (116)	22 (98)	22 (98)	
Up	Rt. hand	14 (62)	18 (80)	24 (107)	20 (89)	20 (89)	Values given represent maximum exertable force in pounds (Newtons) by the 5 percentile man.
	Lft. hand	9 (40)	15 (67)	17 (76)	17 (76)	15 (67)	
Down	Rt. hand	17 (76)	20 (89)	26 (116)	26 (116)	20 (89)	
	Lft. hand	13 (58)	18 (80)	21 (93)	21 (93)	18 (80)	
Outboard	Rt. hand	14 (62)	15 (67)	15 (67)	16 (71)	17 (76)	
	Lft. hand	8 (36)	8 (36)	10 (44)	10 (44)	12 (53)	
Inboard	Rt. hand	20 (89)	20 (89)	22 (98)	18 (80)	20 (89)	
	Lft. hand	13 (58)	15 (67)	20 (89)	16 (71)	17 (76)	

Note: The above results are those obtained from unrestricted movement of the subject. Any force required to overcome garment restriction would reduce the effective forces by the same amount.

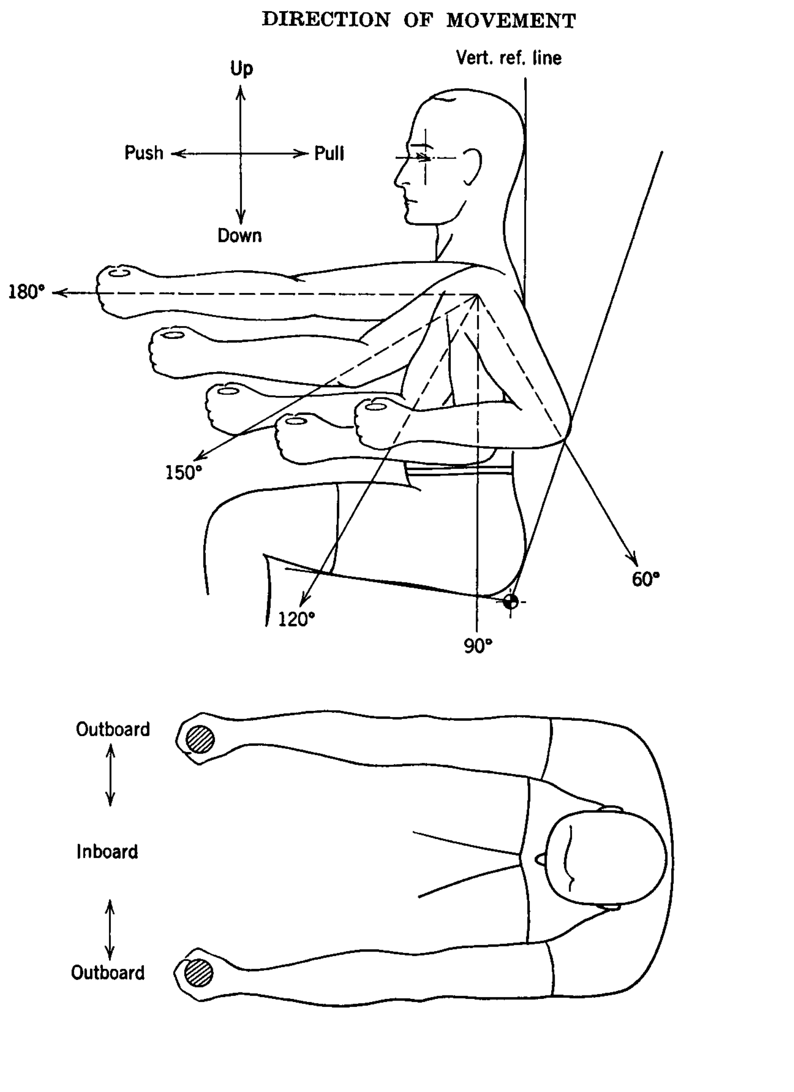


Table 1.3
Rates of Stick Movement in Flight Test Pull-ups Under Various Loads (BuAer, 1954)

Pull-up	*Maximum Stick Load* (*lb*)	(*N*)	*Average Rate of Stick Motion* (*in/s*)	(*cm/s*)	*Time for Full Deflection* (*s*)
1	35	156	51.85	131.70	0.162
2	74	329	15.58	39.57	0.475
3	77	343	11.00	27.94	0.600
4	97	431	10.27	26.09	0.750

The care exercised in considering the human element in the closed-loop system made up of pilot and aircraft can determine the success or failure of a given aircraft design to complete its mission in a safe and efficient manner.

Many critical tasks performed by pilots involve them in activities that resemble those of a servo control system. For example, the execution of a landing approach through turbulent air requires the pilot to monitor the aircraft's altitude, position, attitude, and airspeed and to maintain these variables near their desired values through the actuation of the control system. It has been found in this type of control situation that the pilot can be modeled by a linear control system based either on classical control theory or optimal control theory (Etkin, 1972; Kleinman et al., 1970; McRuer and Krendel, 1973).

1.5 Handling Qualities Requirements

As a result of the inability to carry out completely rational design of the pilot–machine combination, it is customary for the government agencies responsible for the procurement of military airplanes, or for licensing civil airplanes, to specify compliance with certain "handling (or flying) qualities requirements" (e.g., ICAO, 1991; USAF, 1980; USAF, 1990). *Handling qualities* refers to those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role (Cooper and Harper, 1969).

These requirements have been developed from extensive and continuing flight research. In the final analysis they are based on the opinions of research test pilots, substantiated by careful instrumentation. They vary from country to country and from agency to agency, and, of course, are different for different types of aircraft. They are subject to continuous study and modification in order to keep them abreast of the latest research and design information. Because of these circumstances, it is not feasible to present a detailed description of such requirements here. The following is intended to show the nature, not the detail, of typical handling qualities requirements.[4] Most of the specific requirements can be classified under one of the following headings.

CONTROL POWER

The term *control power* is used to describe the efficacy of a control in producing a range of steady equilibrium or maneuvering states. For example, an elevator control, which by taking positions between full up and full down can hold the airplane in equilibrium at all speeds in its speed range, for all configurations[5] and CG positions, is a powerful control. On the other hand, a rudder that is not capable at full deflection of maintaining equilibrium of yawing moments in a condition of one engine out and negligible sideslip is not powerful enough. The handling qualities requirements normally specify the specific speed ranges that must be achievable with full elevator de-

[4]For a more complete discussion, see AGARD (1959); Stevens and Lewis (1992).

[5]This word describes the position of movable elements of the airplane—for example, landing configuration means that landing flaps and undercarriage are down, climb configuration means that landing gear is up, and flaps are at take-off position, and so forth.

flection in the various important configurations and the asymmetric power condition that the rudder must balance. They may also contain references to the elevator angles required to achieve positive load factors, as in steady turns and pull-up maneuvers (see "elevator angle per g," Sec. 3.1).

CONTROL FORCES

The requirements invariably specify limits on the control forces that must be exerted by the pilot in order to effect specific changes from a given trimmed condition, or to maintain the trim speed following a sudden change in configuration or throttle setting. They frequently also include requirements on the control forces in pull-up maneuvers (see "control force per g," Sec. 3.1). In the case of light aircraft, the control forces can result directly from mechanical linkages between the aerodynamic control surfaces and the pilot's flight controls. In this case the hinge moments of Sec. 2.5 play a direct role in generating these forces. In heavy aircraft, systems such as partial or total hydraulic boost are used to counteract the aerodynamic hinge moments and a related or independent subsystem is used to create the control forces on the pilot's flight controls.

STATIC STABILITY

The requirement for static longitudinal stability (see Chap. 2) is usually stated in terms of the *neutral point.* The neutral point, defined more precisely in Sec. 2.3, is a special location of the center of gravity (CG) of the airplane. In a limited sense it is the boundary between stable and unstable CG positions. It is usually required that the relevant neutral point (stick free or stick fixed) shall lie some distance (e.g., 5% of the mean aerodynamic chord) behind the most aft position of the CG. This ensures that the airplane will tend to fly at a constant speed and angle of attack as long as the controls are not moved.

The requirement on static lateral stability is usually mild. It is simply that the spiral mode (see Chap. 6) if divergent shall have a time to double greater than some stated minimum (e.g., 4s).

DYNAMIC STABILITY

The requirement on dynamic stability is typically expressed in terms of the damping and frequency of a natural mode. Thus the USAF (1980) requires the damping and frequency of the lateral oscillation for various flight phases and stability levels to conform to the values in Table 1.4.

STALLING AND SPINNING

Finally, most requirements specify that the airplane's behavior following a stall or in a spin shall not include any dangerous characteristics, and that the controls must retain enough effectiveness to ensure a safe recovery to normal flight.

Table 1.4[1]
Minimum Dutch Roll Frequency and Damping

Level	*Flight Phase Category*	*Class*	*Min* ζ_d*	*Min* $\zeta_d \omega_{n_d}$,* *rad/s*	*Min* ω_{n_d}, *rad/s*
1	A	I, IV II, III	0.19 0.19	0.35 0.35	1.0 0.4
	B	All	0.08	0.15	0.4
	C	I, II-C, IV	0.08	0.15	1.0
		II-L, III	0.08	0.10	0.4
2	All	All	0.02	0.05	0.4
3	All	All	0	—	0.4

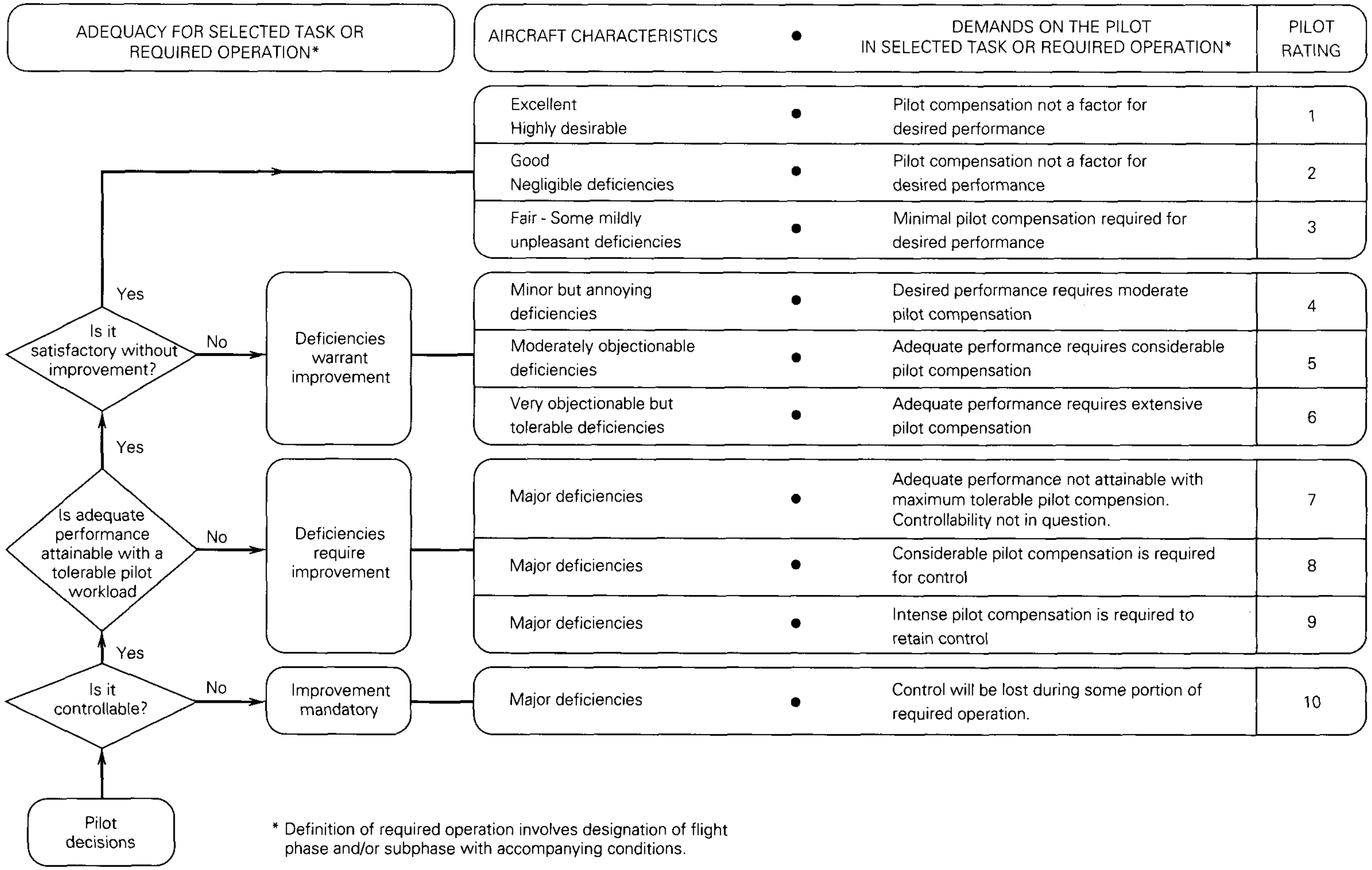
[1]*Level, Phase* and *Class* are defined in USAF, 1980.
**Note:* The damping coefficient ζ, and the undamped natural frequency ω_n, are defined in Chap. 6.

RATING OF HANDLING QUALITIES

To be able to assess aircraft handling qualities one must have a measuring technique with which any given vehicle's characteristics can be rated. In the early days of aviation, this was done by soliciting the comments of pilots after they had flown the aircraft. However, it was soon found that a communications problem existed with pilots using different adjectives to describe the same flight characteristics. These ambiguities have been alleviated considerably by the introduction of a uniform set of descriptive phrases by workers in the field. The most widely accepted set is referred to as the "Cooper-Harper Scale," where a numerical rating scale is utilized in conjunction with a set of descriptive phrases. This scale is presented in Fig. 1.4. To apply this rating technique it is necessary to describe accurately the conditions under which the results were obtained. In addition it should be realized that the numerical pilot rating (1–10) is merely a shorthand notation for the descriptive phrases and as such no mathematical operations can be carried out on them in a rigorous sense. For example, a vehicle configuration rated as 6 should not be thought to be "twice as bad" as one rated at 3. The comments from evaluation pilots are extremely useful and this information will provide the detailed reasons for the choice of a rating.

Other techniques have been applied to the rating of handling qualities. For example, attempts have been made to use the overall system performance as a rating parameter. However, due to the pilot's adaptive capability, quite often he can cause the overall system response of a bad vehicle to approach that of a good vehicle, leading to the same performance but vastly differing pilot ratings. Consequently system performance has not proved to be a good rating parameter. A more promising approach involves the measurement of the pilot's physiological and psychological state. Such methods lead to objective assessments of how the system is influencing the human controller. The measurement of human pilot describing functions is part of this technique (Kleinman et al., 1970; McRuer and Krendel, 1973; Reid, 1969).

Research into aircraft handling qualities is aimed in part at ascertaining which vehicle parameters influence pilot acceptance. It is obvious that the number of possi-



* Definition of required operation involves designation of flight phase and/or subphase with accompanying conditions.

Figure 1.4 Handling qualities rating scale; Cooper/Harper scale (Cooper and Harper, 1969).

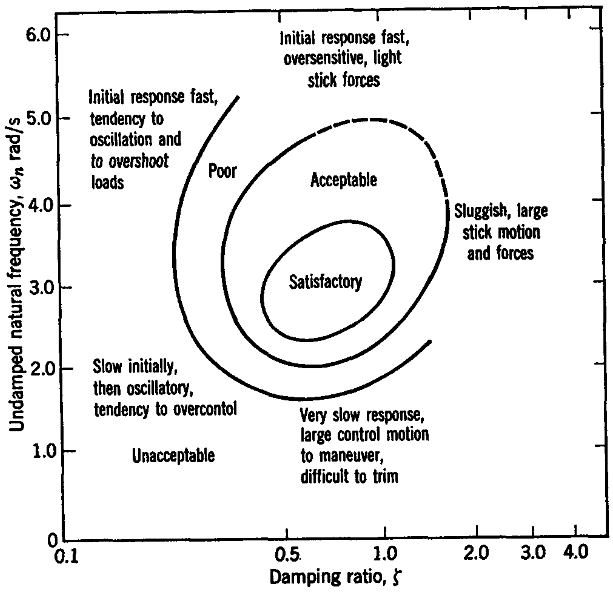


Figure 1.5 Longitudinal short-period oscillation—pilot opinion contours (O'Hara, 1967).

ble combinations of parameters is staggering, and consequently attempts are made to study one particular aspect of the vehicle while maintaining all others in a "satisfactory" configuration. Thus the task is formulated in a fashion that is amenable to study. The risk involved in this technique is that important interaction effects can be overlooked. For example, it is found that the degree of difficulty a pilot finds in controlling an aircraft's lateral-directional mode influences his rating of the longitudinal dynamics. Such facts must be taken into account when interpreting test results. Another possible bias exists in handling qualities results obtained in the past because most of the work has been done in conjunction with fighter aircraft. The findings from such research can often be presented as "isorating" curves such as those shown in Fig. 1.5.

1.6 Axes and Notation

In this book the Earth is regarded as flat and stationary in inertial space. Any coordinate system, or *frame of reference*, attached to the Earth is therefore an inertial system, one in which Newton's laws are valid. Clearly we shall need such a reference frame when we come to formulate the equations of motion of a flight vehicle. We denote that frame by $F_E(O_E, x_E, y_E, z_E)$. Its origin is arbitrarily located to suit the circumstances of the problem, the axis $O_E z_E$ points vertically downward, and the axis $O_E x_E$, which is horizontal, is chosen to point in any convenient direction, for example, North, or along a runway, or in some reference flight direction. It is additionally assumed that gravity is uniform, and hence that the mass center and center of gravity (CG) are the same point. The location of the CG is given by its Cartesian coordinates relative to F_E. Its velocity relative to F_E is denoted $\mathbf{V}^E$ and is frequently termed the *groundspeed.*

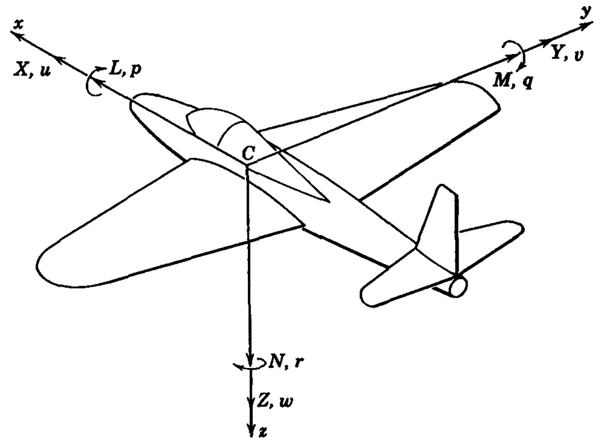


Figure 1.6 Notation for body axes. L = rolling moment, M = pitching moment, N = yawing moment, p = rate of roll, q = rate of pitch, r = rate of yaw. $[X, Y, Z]$ = components of resultant aerodynamic force. $[u, v, w]$ = components of velocity of C relative to atmosphere.

Aerodynamic forces, on the other hand, depend not on the velocity relative to F_E, but rather on the velocity relative to the surrounding air mass (the *airspeed*), which will differ from the groundspeed whenever there is a wind. If we denote the wind velocity vector relative to F_E by **W**, and that of the CG relative to the air by **V** then clearly

$$\mathbf{V}^E = \mathbf{V} + \mathbf{W} \tag{1.6,1}$$

The components of **W** in frame F_E, that is, relative to Earth, are given by

$$\mathbf{W}_E = [W_x \; W_y \; W_z]^T \tag{1.6,2}$$

V represents the magnitude of the airspeed (thus retaining the usual aerodynamics meaning of this symbol). For the most part we will have $\mathbf{W} = 0$, making the airspeed the same as the inertial velocity.

A second frame of reference will be needed in the development of the equations of motion. This frame is fixed to the airplane and moves with it, having its origin C at the CG, (see Fig. 1.6). It is denoted F_B and is commonly called body axes. Cxz is the plane of symmetry of the vehicle. The components of the aerodynamic forces and moments that act on the airplane, and of its linear and angular velocities relative to

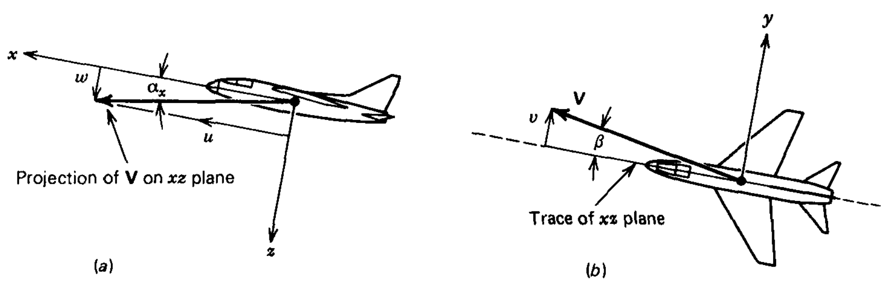


Figure 1.7 (*a*) Definition of α_x. (*b*) View in plane of y and **V**, definition of β.

the air are denoted by the symbols given in the figure. In the notation of Appendix A.1, this means, for example, that

$$\mathbf{V}_B = [u\ v\ w]^T \tag{1.6,3}$$

The vector **V** does not in general lie in any of the coordinate planes. Its orientation is defined by the two angles shown in Fig. 1.7:

$$\begin{aligned} &\text{Angle of attack,} \qquad \alpha_x = \tan^{-1}\frac{w}{u} \\ &\text{Angle of sideslip,} \qquad \beta = \sin^{-1}\frac{v}{V} \end{aligned} \tag{1.6,4}$$

With these definitions, the sideslip angle β is not dependent on the direction of Cx in the plane of symmetry.

The symbols used throughout the text correspond generally to current usage and are mainly used in a consistent manner.