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Introduction to Aerial Vehicle Flight Mechanics, Stability and Control

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Abstract

This article provides an introduction to Section 5.1 on flight mechanics and dynamics, stability and control, and navigation. It introduces some basic concepts of flight control, and static and dynamic stability. Some particular features of vertical or short take-off and landing (V/STOL) aircraft flight control, not covered elsewhere in this Section, are discussed briefly. The other articles in this Section are introduced.

1. Background

Section 5.1 covers a number of topics in the areas of flight mechanics, flight dynamics, stability and control, and navigation, all applied to various types of aerial vehicles: fixed-wing and rotary-wing, inhabited and uninhabited, civil and military. This article is intended to set the scene for the subsequent articles in Section 5.1. Thus, it will cover some fundamental aspects of aerial vehicle stability and control, discuss some special features of vertical or short take-off and landing (V/STOL) aircraft flight control, not covered elsewhere in this Section, and introduce the subsequent articles.

2. The six degrees of freedom

Any aerial vehicle has six degrees of freedom, that is, it is free to move in three mutually-perpendicular directions (forwards/backwards, up/down and sideways) and to rotate about three mutually-perpendicular axes (roll, yaw and pitch). These six degrees of freedom, together with appropriate axes and notation, are illustrated in eae258 for a typical fixed-wing aircraft and in eae261 for a guided weapon. Before proceeding, some terminology used later in this article will be briefly defined. The controls in the pilot's cockpit (the stick or yoke, rudder pedals etc) are referred to here as *inceptors*. The control surfaces on the airframe (ailerons, elevators etc) are referred to as *effectors*.

It is unusual for any aerial vehicle to offer individual control of each of these six degrees of freedom. Thus, on a traditional fixed-wing aircraft, as discussed in eae258, the pilot will be able to control the roll (using the ailerons), the pitch (using the elevators), the yaw (using the rudder) and longitudinal acceleration (using the engine throttle). These controls are illustrated in eae252. Note that there is not normally any direct control of lateral or vertical motions, which are instead produced as a result of roll and pitch respectively.

Guided weapons generally follow the control concept described above but, as described in eae261, there are exceptions to this. It is possible to generate direct sideforce or normal force variation, either with rocket thrusters located close to the centre of gravity (cg) – eg Aster - or with a cruciform arrangement of variable-incidence wings close to the cg.

Traditional single-rotor helicopters, as discussed in eae259, offer the pilot direct control of normal force (via the main rotor collective pitch control), lateral and longitudinal force (via the main rotor cyclic pitch control) and yaw (via the tail rotor collective control). Pitching and rolling moments are not directly controlled but are side effects of the application of longitudinal or lateral cyclic, respectively.

On multi-rotor helicopters the controls are similar to the above but with subtle differences in implementation. Thus, yaw control is achieved through the yaw pedals applying differential cyclic pitch to the two main rotors (tilting the two rotor discs in opposite directions) if in tandem or side-by-side configuration, or differential collective pitch to the rotors (to produce differential torques between the two rotors) if in co-axial configuration. On tandem rotor helicopters, application of longitudinal (fore and aft) cyclic pitch is supported by differential collective pitch to help generate a pitching moment on the airframe. Similarly, on side-by-side rotor aircraft application of lateral (sideways) cyclic pitch is supported by differential collective pitch to help generate a rolling moment.

Compound helicopters feature the addition of fixed wings (for extra lift at high speeds) and/or propulsors (for extra thrust). Such approaches are generally used to overcome the limited maximum speed capability of a conventional helicopter (see eae251). One side effect of fitting a propulsor, however, is that longitudinal translation can then be de-coupled from airframe pitching, offering potential control and manoeuvrability advantages over a conventional configuration.

3. Aerial vehicle stability

Aerial vehicle stability is concerned with the vehicle’s behaviour following a disturbance from the equilibrium condition. Static stability is concerned with the initial tendency of the vehicle to return to its equilibrium condition, whereas dynamic stability is concerned with the ensuing motion. To simplify the analysis of aerial vehicle stability, it is usual to consider the vehicle motions described above in two groups: longitudinal motions and lateral/directional motions. The longitudinal plane, or symmetry plane, contains the aircraft’s longitudinal (fuselage) axis and the vertical fin; this plane is vertical when the aircraft is flying straight and level. Longitudinal motions include pitching, and linear motions along the longitudinal (fore and aft) and heaving (up and down) axes. The lateral plane contains the aircraft’s longitudinal (fuselage) axis and the wings (assuming no dihedral); this plane is horizontal when the aircraft is flying straight and level. Lateral motions include roll, sideslip and yaw (see, for example, Hancock, 1995). Note that some authors refer to yaw as a directional motion (Anderson, 2000).

3.1 Static Stability

Static stability is merely concerned with the initial response of an aerial vehicle to a disturbance. The classes of static stability are defined as follows.

- Stable (also referred to as positive stability) - the vehicle tends to return to its equilibrium condition after a disturbance.
- Neutrally stable - the vehicle remains in its disturbed condition.
- Unstable (also referred to as negative stability) - the vehicle tends to move further away from its equilibrium condition in the same direction as the initial disturbance.

These three conditions are illustrated in Figure 1 for an aft-tailed, fixed-wing aerial vehicle of fixed geometry but variable centre of gravity (cg) position. In each case the vehicle is in trim before the disturbance occurs.

< Fig 1 near here >

The effect of a pitching disturbance (caused, for example, by an up-gust) is to increase the lift of both wing and tail surfaces. The line of action of the resultant of the two lift forces passes through a point on the longitudinal axis of the aerial vehicle known as the *neutral point* (i.e. the aerodynamic centre of the whole vehicle) and it is the relationship between the position of this point and the vehicle cg that determines whether or not the vehicle is statically stable. This distance is called the *static margin* and it is positive if the neutral point is aft of the cg, i.e. if the vehicle is statically stable.

3.2 Dynamic stability

Dynamic stability is concerned with the time-history of the motion of a vehicle following a disturbance from the equilibrium condition. Any detailed analysis of aerial vehicle motion is necessarily highly complex because of the inherent non-linearity in the aerodynamic quantities, including cross-couplings (see eae254, eae255 and eae257) and the six spatial degrees of freedom that the vehicle has (see above).

Nevertheless, for small perturbations, linearity can be assumed and cross-coupling effects are small. It is therefore possible to gain some insight into vehicle dynamic behaviour without introducing these complications. As with static stability, the motion is identified as stable, neutrally stable or unstable but there are two basic types of motion possible — *periodic* and *aperiodic*. Dealing with the second of these first, and for a single degree of freedom system, the responses of systems classified as above are shown in Figure 2.

< Fig 2 near here >

It is clear that, where the system is non-oscillatory, dynamic and static stability are qualitatively identical. A measure of dynamic stability or instability is provided by the time for the amplitude of the motion to change to one half of (stable), or double (unstable), the amplitude of the original disturbance.

In the case of oscillatory motion (Figure 3), the motion may be convergent (damped), neutral or divergent corresponding to the classes of stability already described. Note that all cases illustrated are statically stable; static stability is therefore a necessary but not sufficient condition for dynamic stability.

< Fig 3 near here >

4. V/STOL aircraft stability and control

Subsequent Chapters in this Section will consider fixed-wing static (eae252 and eae253) and dynamic (eae254 and eae255) stability, and rotary-wing static (eae256) and dynamic (eae257) stability. Similarly, fixed-wing (eae258) and rotary-wing (eae259) control and handling qualities are discussed. There are some aerial vehicles, however, that exhibit some of the characteristics of both fixed- and rotary-wing aircraft; these are V/STOL aircraft - aircraft capable of hover and vertical flight as well as fixed-wing forward flight. Two particular cases will be considered here to illustrate some of the special issues of such vehicles: a tiltrotor such as the Bell Boeing V-22 Osprey (see Figure 4) and a jet-lift V/STOL aircraft such as the Hawker Siddeley Harrier and its derivatives.

< Fig 4 near here >

4.1 Rotary-wing V/STOL

The Bell Boeing V-22 Osprey can be described as a convertiplane, that is it can convert between rotary-wing and fixed-wing flight modes by tilting the engine and rotor assemblies at the tips of its fixed wings. Similar convertiplane concepts, flown as concept demonstrators in the past, are tilt-wings, where the entire wing, engine and rotor assemblies rotate between helicopter and fixed-wing modes. Tilt-wings overcome one particular problem that tilt-rotors experience - download on the wings (possibly as much as 30% of rotor thrust) caused by rotor downwash - but at the expense of a very limited transition corridor. As a tilt-wing aircraft decelerates from wing-borne flight to the hover it must rotate its rotors towards the helicopter mode to generate a vertical component of thrust. In doing so, the wing is put to an increasingly high angle of attack, generating a large lift force that causes the aircraft trajectory to “balloon” and approaching stall. The combination of flight speed, flight trajectory and wing angle must, therefore, be very carefully controlled with a tilt-wing aircraft. One concept to overcome both this problem and the tiltrotor wing download problem was explored in the European "Erica" project - only tilting the part of the wing in the rotor downwash.

The discussion above illustrates the key to any successful V/STOL aircraft design, which is the transition between hover and up-and-away flight. Making this process intuitive and easily controllable for the pilot imposes demands on the airframe and control system designers. The tiltrotor concept lends itself to a simple transition process - tilting the rotors (also called proprotors because of their dual function) and, hence, vectoring the thrust. As explained earlier in this article, however, the controls in fixed- and rotary-wing aircraft are different in concept and operation, so there is a need to blend between the two different control regimes during flight transition. Figure 5 shows the control effectors for the V-22 in helicopter mode, whereas Figure 6 shows the same for fixed-wing mode.

< Fig 5 near here >
< Fig 6 near here >

During vertical takeoff, conventional helicopter controls are used (see above, and eae251 & eae259). As the aircraft gains forward speed (between about 40 and 80 knots), the wing begins to produce lift and the fixed-wing controls (ailerons, elevators, and rudders) become effective. The rotary-wing controls are then gradually phased out by the flight control system. At approximately 100 to 120 knots, the wing is fully effective and pilot control of cyclic pitch of the proprotors is “locked out”. The conversion corridor is claimed to be very wide in both accelerating and decelerating flight, with a latitude of approximately 100 knots (Bell Boeing, 2010). This wide corridor results in a safe and comfortable transition, away from the danger of wing stall. Vertical descents, however, have to be carefully managed because of the danger of asymmetric vortex ring conditions (see eae251).

The primary flight control inceptors on the V-22 consist of a cyclic stick, a collective (or thrust control) lever, yaw pedals and a proprotor nacelle angle control (a thumbwheel on the collective lever). In helicopter mode pushing the cyclic stick forward will cause the two proprotor discs (not the nacelles) to tilt forwards producing a forward acceleration, a nose-down pitching moment and (from the hover) a climb as speed increases (because of the shape of the power vs speed curve – see eae251). In fixed-wing mode the same pilot control action will deflect the elevators down, producing a nose-down pitching moment and an acceleration as the aircraft starts to dive. If the cyclic stick is pushed to the right then, in helicopter mode, this tilts the two proprotor discs to the right, increases the collective pitch of the left-hand rotor, reduces the collective pitch of the right-hand rotor and produces a roll to the right. In fixed-wing mode the same pilot control movement deflects the left-hand flaperon (a wing trailing-edge control effetor that can operate anti-symmetrically as an aileron or symmetrically as a flap) down and the right-hand flaperon up, producing a roll to the right. The yaw pedals apply differential cyclic control to the two proprotors in helicopter mode, tilting the two rotor discs (not the nacelles) in opposite directions to produce yaw, whereas in fixed-wing mode they operate the rudders to produce the same effect. Raising the collective lever increases the angle of attack of all the rotor blades in helicopter mode. As in a conventional helicopter this increases thrust and rotor power (because the increased rotor blade drag requires extra power to maintain rotor speed and a governor ensures that this speed is maintained) and acts to increase aircraft altitude. In fixed-wing mode the same lever acts to control propeller (proprotor) blade pitch and engine power. It therefore acts to adjust aircraft speed. Note that in conventional helicopter controls *raising* the collective lever increases thrust and engine power; in conventional fixed-wing controls *pushing* the throttle lever(s) would increase engine thrust and power.

4.2 Jet-lift V/STOL

Jet-lift V/STOL flight is divided into a number of regimes depending on the dominant lift-generating mechanism. Hover and low-speed flight (up to about 35 knots) is jet-borne. High-speed flight is wing-borne. Forward flight between 35 knots and transition to wing-borne flight (nominally at 140 knots but anywhere from about 90 to 180 knots) is described as semi-jet-borne. In this regime aircraft weight is supported by a component of jet thrust plus wing lift. Note that the conversion airspeed (V_{con}) - the airspeed at which an accelerating transition is complete and the aircraft enters wing-borne flight - is not necessarily V_{stall} because angle of attack levels in semi-jet-borne flight are less than α_{MAX}.

A key design decision for jet-lift V/STOL aircraft is how to provide flight control effectors for hover and low speeds, when the aerodynamic controls are ineffective. One solution, pioneered in the Hawker Siddeley Harrier was the use of engine bleed air ducted to puffer jets in the aircraft extremities (nose, tail and wing tips) to provide pitch, roll and yaw control. The same control inceptors (the pilot's stick and rudder pedals) could then be used for the same effects (pitching, rolling or yawing) as in wing-borne flight. One penalty of this system is the adverse impact on the engine performance caused by extracting compressor mass flow away from the engine. On the Harrier, this bleed air is taken from the high-pressure (HP) compressor to maximise the energy in the gases, thereby minimising the size and weight of the ducting required. Taking this HP bleed air causes the turbine entry temperature to rise. The Lockheed Martin F-35B Lightning II, and its predecessor the X-35B Joint Strike Fighter, minimised these problems by splitting the jet-lift functions between four thrust "posts" – the main engine exhaust at the rear, the lift-fan exhaust at the front and two mid-wing-span "roll posts" which also contribute to vertical thrust. Yaw is thus achieved by vectoring the main engine nozzle laterally (something not available to the Harrier with its fore- and aft-vectoring nozzles); pitch is achieved by varying the thrust split between front and rear nozzles (using nozzle area variation, again not available to the Harrier with its light-weight fixed-area nozzle design); and roll is achieved by varying the thrust split between the two roll nozzles (again using variable nozzle area – the Harrier used a similar system but had to include an upward thrust capability for each roll jet to give sufficient roll authority). The gas bled to the roll posts comes from the low-pressure (LP) compressor, which has less impact on the engine performance (than taking HP air) but at the expense of bigger ducting. (The impact of this ducting is minimised by only having to provide it to the roll posts in the wings.) Other examples of control effectors for jet-lift V/STOL aircraft are discussed in eae492.

Transition from jet-borne to wing-borne flight is relatively straightforward in thrust-vectoring aircraft such as the Harrier. The pilot is provided with one extra control over those in a conventional fixed-wing aircraft – a "nozzle lever" which controls nozzle vector angle. Pushing this lever forwards vectors the nozzles aft and causes the aircraft to accelerate. There are, however, a number of stability and control problems peculiar to jet-lift V/STOL aircraft. One of these is associated with intake momentum drag (see eae486) and is the dominant contributor to the powered-lift stability derivatives in hover and low-speed flight. This drag component acts forward of the aircraft cg, in a cross-wind it therefore has a lateral component which is destabilising in yaw. At reasonably high flight speeds (above about 40-70 knots for the Harrier) the stabilising influence of the fin is sufficient to overcome this and provide positive yaw stability. Below this critical flight speed, however, the aircraft is unstable in yaw. This is exacerbated by the high-set, swept wing's dihedral effect (see eae253), which causes the aircraft to roll away from a side-wind, and by the fountain flow roll instability described below. The pilot, therefore, has to be very careful not to let the relative wind direction get too far from head on in the hover, otherwise the aircraft will yaw and roll away from the side-wind, causing a fatal loss of vertical thrust. This effect was the cause of a number of early Harrier accidents and the aircraft was consequently fitted with a wind vane, on the nose just forward of the cockpit, to give the pilot a visible indication of the relative wind direction.

Other stability and control issues peculiar to jet-lift aircraft are associated with jet-induced aerodynamic effects, which are significant contributors to the powered-lift stability derivatives in jet-borne and partially jet-borne flight (up to about 100 knots). Any jet exhausting into quiescent air will entrain ambient air, thereby setting up an induced flow field (see eae492). On a conventional aircraft this entrainment flow field is generally in the freestream direction so it does not cause major stability and control problems. On a jet-lift V/STOL aircraft, however, the lift jets can be directed downwards (in jet-borne flight) or downwards and backwards (in semi-jet-borne flight) causing the entrainment flowfield to impact on the airframe, wings and control surfaces. At its simplest, this entrainment flowfield causes a download on the airframe (known as suckdown), which must be overcome by engine thrust. Out of ground effect this download can be as much as 20% of the engine thrust for a single nozzle located near the wing leading edge. Note, however, that for a well-designed jet-lift aircraft this is more likely to be 5%. In ground effect the lift jets strike the ground and spread out radially, forming a so-called wall jet (or jet ground sheet) with a large surface area and dramatically increased entrainment flow field. Between multiple lift jets, however, the inward-flowing parts of the wall jet will meet and turn upwards to form a so-called fountain flow (see eae492). This fountain flow will impinge on the underside of the aircraft fuselage, providing an up-thrust that acts partially to counteract the suckdown. (The Harrier features strakes and air dams under the fuselage to capture this fountain flow - and prevent it from entering the engine, where the hot gas ingestion can cause thrust loss). If the aircraft adopts a roll attitude then the fountain flow can impinge on the lower surface of one wing, rather than the fuselage, causing a large, destabilising rolling moment.

In general, the jet entrainment flowfield will significantly change a V/STOL aircraft's pitching moment at a given airspeed. Wind tunnel testing must be conducted, therefore with representative jets simulated. There is also a mutual interference between jet and intake flowfields (see Saddington and Knowles, 1999), which is generally (at least partially) accounted for with separate forebody/intake model tests.

Because of the reliance on the engine for flight control in the jet-borne and semi-jet-borne flight regimes, employing an integrated flight and propulsion control (IFPC) system is attractive. An IFPC gives seamless integration of the aerodynamic and propulsive control effectors throughout the flight envelope. The aim of such a system is: to reduce pilot workload by improving flying qualities; to provide the pilot with intuitive cockpit control inceptors and cockpit displays; and to increase aircraft performance (e.g. maximum roll rate at high angles of attack, maximum thrust, reduced fuel consumption). In general such a control system could also provide a vehicle management system with the ability to reconfigure the control effectors. For a V/STOL aircraft in jet-borne or semi-jet-borne flight, however, there are no alternative effectors so reconfiguration possibilities are limited. Failures usually result in degraded performance and a catastrophic control effector failure is difficult to overcome (the best outcome may be controlled ejection).

5. Conclusion

This article has introduced some basic concepts of aerial vehicle flight mechanics, stability and control. The rest of Section 5.1 will expand on these topics, as well as aircraft navigation. The next five articles are concerned with fixed-wing flight mechanics. eae246 considers take-off and landing of fixed-wing aircraft, including special characteristics of fixed-wing naval aviation and the use of ski-jumps for increasing the payload-range performance of jet-lift V/STOL aircraft when operating in STOVL mode (short take-off and vertical landing). Climb and descent of fixed-wing aircraft is considered in eae247, before cruise performance is discussed in eae250. Manoeuvre of fixed-wing aircraft is considered in two articles: eae248 looks at manoeuvre of transport aircraft (primarily level turns and pull-ups) whilst eae249 considers special features of combat aircraft manoeuvring, including energy considerations, metrics for assessing combat manoeuvre performance and the benefits of thrust vectoring. The essentials of rotary-wing flight mechanics are considered in eae251.

Flight dynamics are covered in six articles: four on aspects of fixed-wing flight dynamics and two on rotary-wing flight dynamics, covering static and dynamic stability as described above. Fixed-wing flight dynamics are broken down into longitudinal and lateral/direction modes, as discussed earlier in this article. Longitudinal static stability is covered in eae252, followed by fixed-wing lateral/directional static stability in eae253. Fixed-wing dynamic stability is covered in the next two articles – longitudinal dynamic stability in eae254 and lateral/directional stability in eae255. Rotary-wing static and dynamic stability is covered in eae256 and eae257, respectively. These articles include discussion of some aspects of the important topic of flight test evaluation of helicopter stability.

The early part of this article outlined the key differences between fixed-wing, rotary-wing and guided weapon control. More detail is provided by three of the following articles. Fixed-wing control and handling qualities are discussed in eae258, with particular emphasis on handling qualities assessment and modelling. Rotary-wing control and handling qualities are then discussed in eae259. Special features of guided weapon stability and control are investigated in eae261. Key aspects here are the freedom of vehicle orientation provided by not having a pilot on board and the capability and frequent requirement for high lateral accelerations.

The final two articles in Section 5.1 discuss aspects of aerial vehicle navigation and guidance. General principles of aircraft navigation are covered in eae262, whilst eae263 looks at special features of guided weapon and uninhabited air vehicle (UAV) navigation and path planning.

The present article has also looked at special features of V/STOL aircraft stability and control, both for rotary-wing and for fixed-wing jet-lift aircraft. Such aircraft generally need an additional inceptor for the pilot to control the thrust vector. The main challenge for the control system designer is then to blend the pilot's controls between vertical flight and forward flight modes, whilst minimising pilot workload and providing sufficient control authority to overcome some instabilities unique to this class of aerial vehicle.

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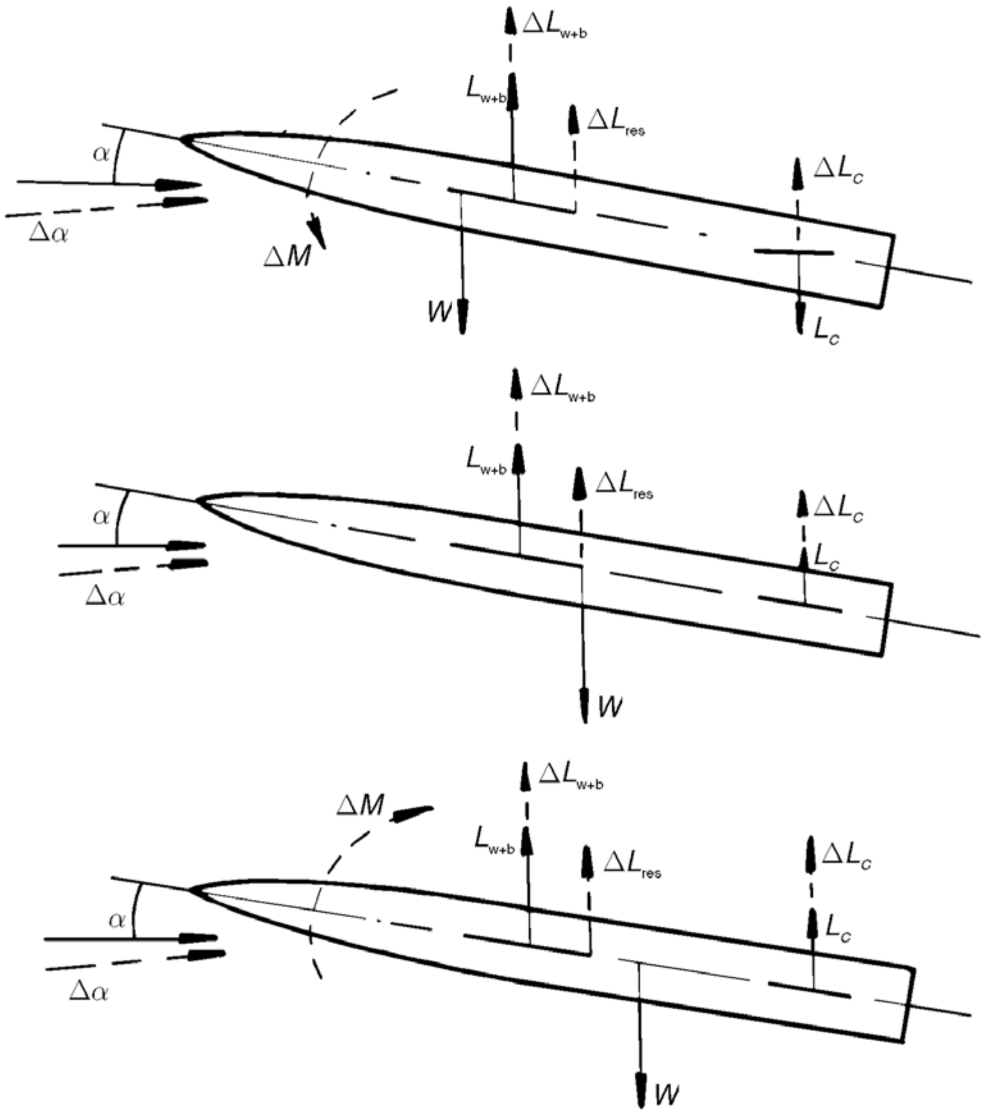

Figure 1: Three cases of longitudinal static stability: stable; neutral; unstable

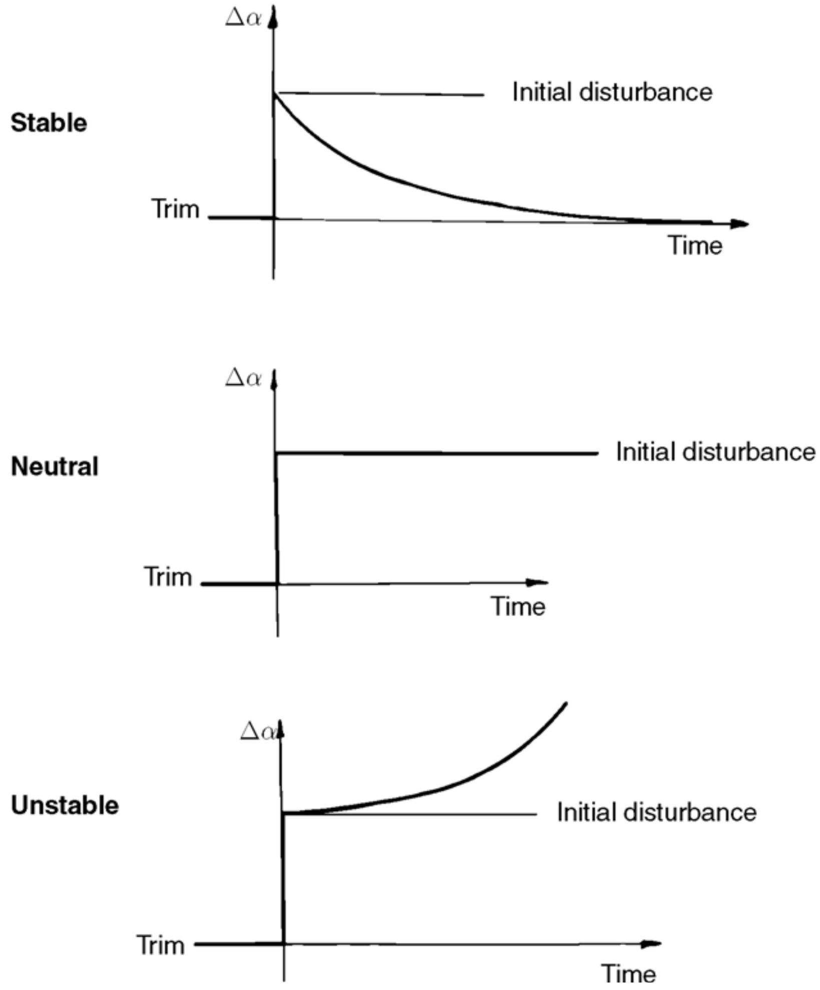

Figure 2: The three categories of aperiodic dynamic stability

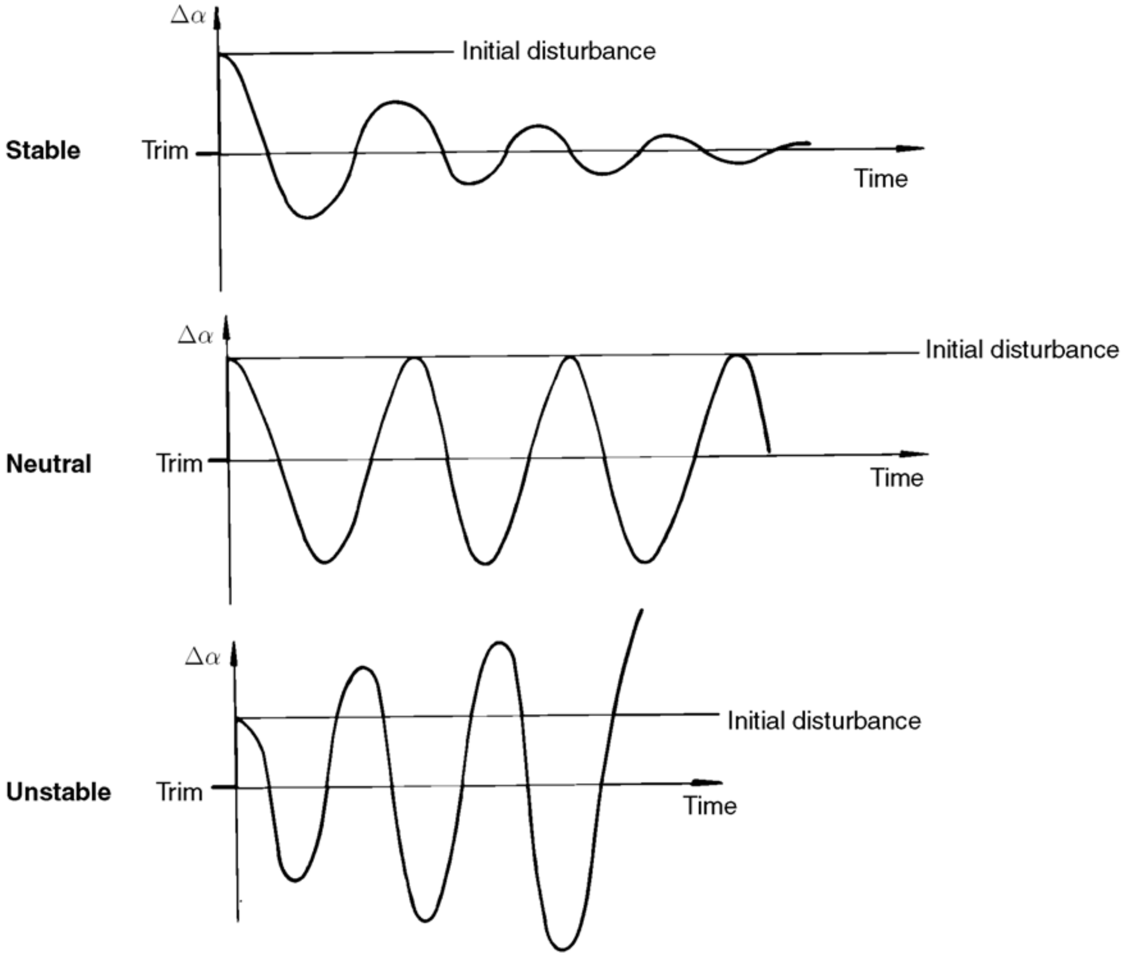

Figure 3: The three categories of periodic dynamic stability

Figure 4: Bell Boeing V-22 Osprey tiltrotor aircraft (photo: author)

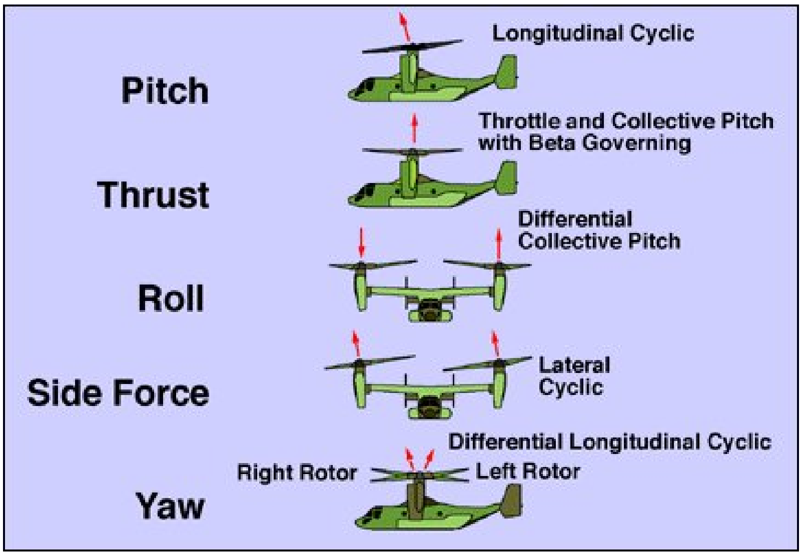

Figure 5: Bell Boeing V-22 tiltrotor control in helicopter mode (courtesy Bell Helicopter)

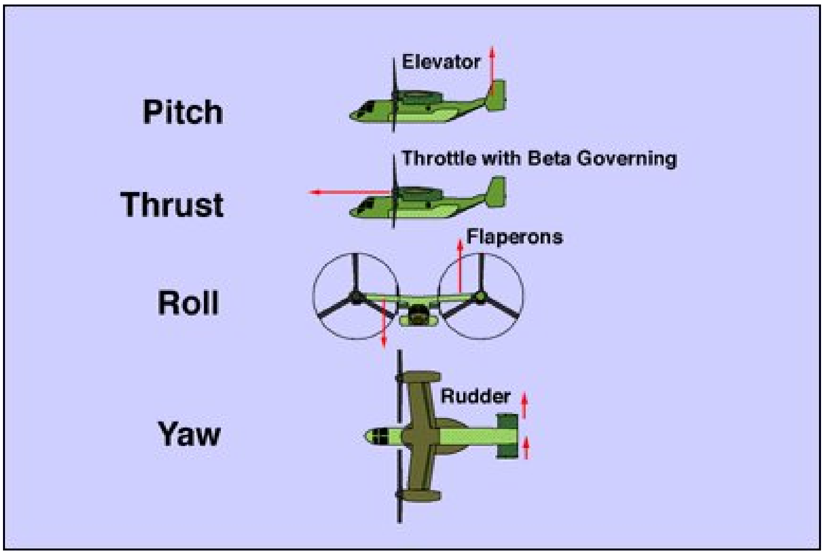

Figure 6: Bell Boeing V-22 tiltrotor control in fixed-wing mode (courtesy Bell Helicopter)

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