Aerobasics – An Introduction to Aeronautics

3. Airplane Basics

S P Govinda Raju

This article introduces the concepts of lift and drag of a wing and their role in determining the performance of an airplane. The airplane is then compared with other modes of transport on the basis of a study by Gabrielli and Von Karman to bring out its special features. Next, the requirements of controlled flight are explained. The relations between the configuration of the airplane and the requirements of controlled flight are indicated.

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1. Wing Aerodynamics

Wing aerodynamics is basic to airplane flight. A wing is a planar body (relatively thin in one direction and extended in the other two) which experiences by reaction with air moving relative to it a large force at right angles to the direction of motion (lift) while suffering a small resistance (drag) directly opposing the motion. For a given wing, both lift and drag depend on the direction of motion which should be nearly but not exactly in the plane of the wing. *Figure* 1 illustrates the concept. The wing is shown in *Figure* 1a and is rectangular with rounded ends. Typically it has a cross-section as shown in *Figure* 1b. The cross-section (called the the wing section or airfoil) is generally blunt in the front (the leading edge) and sharp near the rear end (the trailing edge). The wing is shown at rest in a uniform stream of air moving at a speed V relative to it. Lift and drag forces on the wing in this case are identical to the corresponding forces when the wing moves at the same speed, V, while the air is at rest. This situation is more convenient for study.

Keywords
Lift and drag, transport economy, equilibrium, stability, controllability.

The angle between a reference plane in the wing and the direction of motion is called the incidence or angle of attack, α, and plays a vital role in the generation of lift. *Figure* 1c shows typical

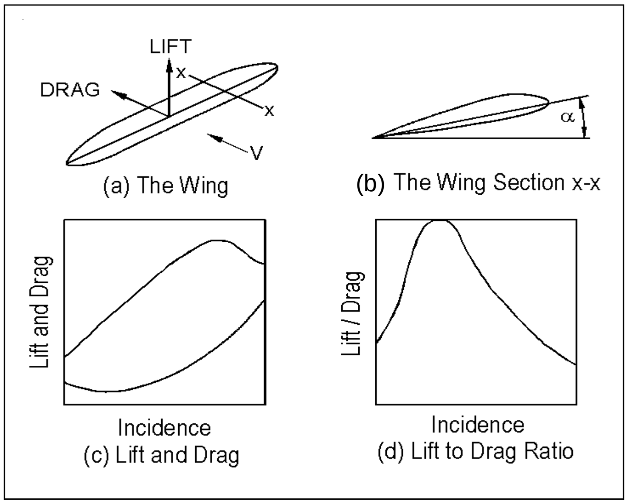

Figure 1. Geometry of a wing and its aerodynamic characteristics.

The component of aerodynamic force on a wing normal to flight direction (lift) is generally much larger than the component along the flight direction (drag) for a wing of cross-section typically as in (b). Both lift and drag depend on the incidence, α, as in (c).The ratio of lift to drag has a large influence on airplane performance.

variations of lift and drag of a wing as the incidence varies. The lift increases with incidence to reach a maximum at some α at which the wing is said to stall. Beyond stall, the lift decreases rapidly. The drag of the wing is relatively smaller than lift and increases rapidly for large α. Thus the ratio of lift to drag, which is critically important to airplane flight, first increases rapidly to a maximum value and then decreases more slowly as in *Figure* 1d. The maximum value of the ratio of lift to drag depends on the shape of the wing in terms of plan form and cross-section. An airplane consists of a wing as well as other parts (like fuselage and vertical fin which contribute very little to lift but increase drag) and may be expected to have a higher drag and thus a lower lift-drag ratio in relation to a wing alone. *Table* 1 shows values of maximum lift to drag ratios typical of several configurations. In level flight of an airplane, lift balances the weight of the airplane while the propulsive force (the thrust of the propeller or the jet thrust from a jet engine) overcomes the drag. A high lift-drag ratio

Table 1. Typical Lift/Drag ratios of various configurations.

Configuration	Maximum Lift/Drag ratio
Airfoil	100-250
Sail plane	20-40
Civil aircraft	12-20
Combat aircraft	7-12

Box 1. Transportation Economy

Any transportation device displaces a weight W horizontally over a distance d while consuming some mechanical energy which is degraded into heat. It is seen that the mechanical energy consumed is the product of resistance to the motion R and the displacement d while the usefulness of the device is measured by the product of weight transported and the distance. One may thus define a measure of transportation economy ε as the ratio of work done to the usefulness of the transport:

$$\varepsilon = \frac{R.d}{W.d} = \frac{R}{W} = \frac{R.V}{W.V} = \frac{P}{W.V} \qquad \text{(i)}$$

In the above, V is the speed of transport. From (i) it is seen that ε can be also be interpreted as the specific resistance (resistance per unit weight) as well as the ratio of power required, P to the rate of transportation, WV. It is to be noted that smaller the ε, the better the mode of transport in terms of energy economy. In the case of the airplane in level flight, $R = D$ and $W = L$ and thus ε is the drag to lift ratio in the level flight condition.

The usefulness of a transport device also depends on the speed of transport V. Different modes of transport operate at different speeds due to economic and other reasons. In general, one may expect that a higher speed of transport entails a higher specific resistance. One may thus compare various transport devices using a plot of ε against V. This comparison was originally done by Gabrielli and Von Karman [1] more than fifty years ago. The study has been updated recently by the Railway Research Group of the Imperial College [2] and is shown in *Figure* A. It may be noted that the actual mechanical power, R times V, is seldom measured and this figure compares the devices on the basis of installed power which is always higher. Thus ε in *Figure* A may be interpreted as a specific tractive effort. Nevertheless, it is clear from the figure that devices like ships and submarines which travel at relatively low speeds have a lower ε as compared to airplanes. Automobiles and airplanes are roughly comparable. It may also be noted that the transportation speed of a land vehicle is much lower and thus an airplane is unmatched in providing an excellent combination of ε and speed and is ideal for long distance transport. However, airplanes are highly capital intensive and are used extensively only in the developed countries. Developing countries like India and China are fast catching up in civil aviation.

Figure A also shows the Gabrielli–Karman (GK) line which was believed to be the upper limit for the efficiency of transport at the time of the study (1950). There have been technological advances in transport devices in the last fifty years and the progress is indicated by the lines for various modes of transport moving closer to the GK line. It is seen that commercial airplanes have made significant gains in transport efficiency and have crossed the GK line indicating substantial progress. One may add here that the latest transport airplane, the A380, claims a fuel efficiency of about 35 passenger kilometers per liter of fuel and this is in the same range as an average passenger car, fully loaded. This is quite remarkable considering that the airplane delivers this fuel efficiency at a flight speed of about 900 km/h as against the automobile with a typical speed about a tenth of this value.

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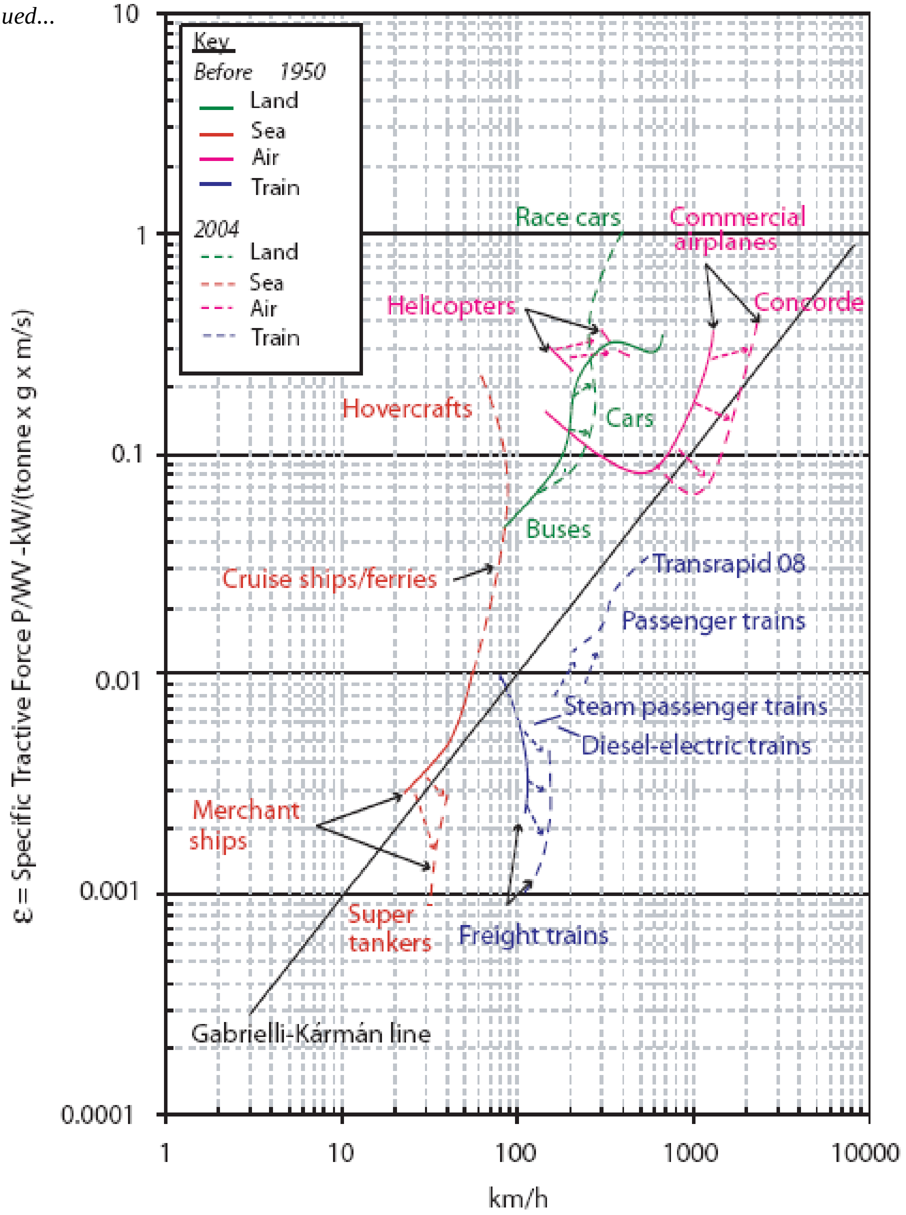

Figure A. Transport economy at different speeds. The specific tractive force, ε, is an indication of transport efficiency (smaller the better). It generally increases with speed, indicating a price to be paid for the higher speed. The study in 1950 by Gabrielli and Von Karman appeared to indicate a lower limit to ε as per the G–K line in the above figure. Several modes of transport have been included in the figure. A recent study [2] shows that many modes of transport have improved in the last 50 years. Civil airplanes have shown a significant improvement by crossing the G–K line.

has a bearing on the efficiency of the airplane as a transportation device.

2. Description of Airplane Motion

For most purposes, an airplane may be considered a rigid body in motion relative to the earth which is static. Earth's rotation about the geographic north-south axis does not play any significant role. The position of an airplane is completely specified by its displacement and orientation relative to a cordinate system fixed on earth. For describing airplane motion we thus need two coordinate systems – one fixed to the earth and the other to the airplane.

The coordinate system fixed to the earth, well known in geography, is the system involving latitudes, longitudes and altitude. This is basically a polar coordinate system fixed at the center of the earth and rotating with it. It is widely used for navigation. An alternative, which is convenient when only short flights are involved, is to choose a system corresponding to the position and orientation of the airplane at a convenient time so that the later positions of the airplane can be related to its initial position. Both these systems are useful.

The coordinate system fixed to the airplane is conveniently chosen with its origin at the center of gravity of the airplane. As all airplanes have a plane of symmetry, it is convenient to have two axes, the OX- and the OZ-axes, in this plane. The OX-axis points forward along the longitudinal direction of the airplane. The OZ-axis points downwards (towards the ground for normal level flight conditions). The OY-axis points towards the right from the pilot's position. The axis system is shown in *Figure* 2. For ease of description, rotations about the OX-, OY- and OZ-axes are respectively named the roll, the pitch, and the yaw and the axes are also called by these names.

In general, an airplane velocity vector has components along the OX-, OY- and OZ-axes. These are denoted by u, v and w. Normal level flight of an airplane is in the plane of symmetry and implies

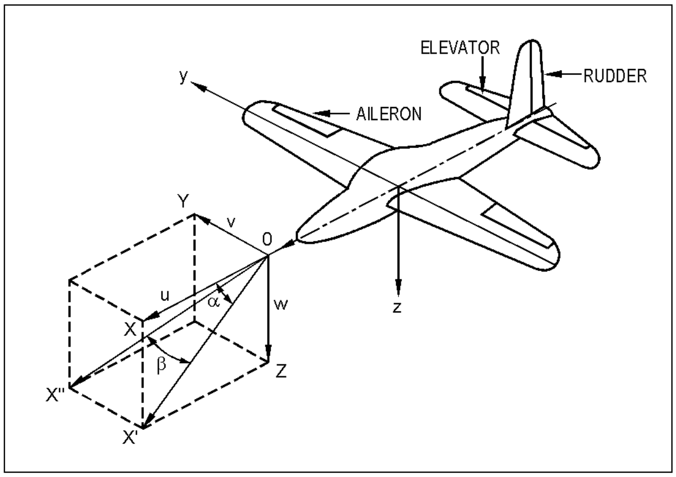

Figure 2. Body-fixed coordinate system for an airplane.
Several coordinate systems with their origins at the centre of gravity of the airplane are useful in flight mechanics. The body axis system is fixed to the airplane. The wind axis system has one axis along the wind direction. The stability axis system, with one axis along the projection of the flight velocity in the plane of symmetry, is useful in stability studies.

that v is zero and u is much larger than w. An alternate description of the velocity vector uses a polar form with the flight speed V, incidence α and sideslip β, as defined in *Figure* 2. Also shown in the figure is the axis OX′ along the projection of the velocity vector in the plane of symmetry. A Cartesian coordinate system using it for one of its axes is called the 'stability-axis system'. This system is obtained by rotating the OX-, OY-, OZ-axis system by an angle α about the OY-axis. The moments and products of inertia of the airplane are constants in the body-axis system OX, OY and OZ. The body-axis system is generally used for computer-based simulation studies of aircraft dynamics. The stability-axis system is useful in the analysis of stability of aircraft motion following a small disturbance. Another axis system with one of its axes, OX″, along the velocity vector is called the 'wind-axis system'. This axis system is obtained by rotating the stability-axis system by an angle β about the OZ′-axis. The aerodynamic forces on an airplane are more easily specified in the wind-axis system. However, this system is not popular as the inertia properties of the airplane are not easily specified in it.

3. Requirements for Controlled Flight

The requirements of controlled flight of an airplane can be conveniently considered under three groups related to equilibrium, stability and controllability.

3.1 *Equilibrium*

Equilibrium implies that a steady level flight of the airplane at the chosen cruise speed can continue indefinitely. This requires that the external forces acting on the airplane be in balance leaving no resultant which can cause acceleration. External forces acting on an airplane in level flight consist of the aerodynamic forces acting on wings and other surfaces, the force of gravity which can be considered as acting at the center of gravity of the airplane, and the propulsive forces due to the operation of the propeller or jet engine as the case may be. Thus 'equilibrium' implies that the total aerodynamic upward force (primarily wing lift) must balance the weight of the aircraft and the total horizontal force along the flight direction (drag) must be balanced by the thrust of the propulsive device. In addition, the pitching moment – the moment about the OY-axis – must be zero. This can be ensured by suitably setting the elevator – a control surface on the horizontal stabilizer shown in *Figure* 2. The balance of other forces and moments – the side force, the rolling moment and the yawing moment – is automatically ensured by the symmetry of the airplane about the XZ-plane. However slight adjustments of the control surfaces – the rudder and the aileron – will ensure this in a real airplane.

Equilibrium implies that a steady level flight of the airplane at the chosen cruise speed can continue indefinitely.

For any wing at a given altitude and wind speed, there is a maximum value of lift at which it stalls. If under these conditions, the weight of the airplane is greater than lift, steady flight is not possible. Thus equilibrium is only possible above a certain flight speed which corresponds to stall. An airplane has to accelerate on the ground to reach the minimum take-off speed which is more than the stall speed (by about 10 to 15%) before it can leave the ground. This needs a runway of about 3.5 km in length for large civil aircraft. This runway length includes a margin for emergency stopping in case of an engine failure.

3.2 *Stability*

Stability implies that, following a disturbance, the aircraft returns to the undisturbed equilibrium state (level flight) after a reasonable length of time without any effort on the part of the pilot. During this period, the airplane may execute complex motions which decay with time. In general, these motions involve changes of pitch, yaw and roll orientations of the airplane as well as motion of the centre of gravity in Y and Z directions.

If the initial disturbance is confined to the XZ-plane, the motion that follows will also be in this plane, the longitudinal plane of the airplane. This motion will involve rotational motion in pitch only. If due to the disturbance there is an increase in incidence, $\Delta\alpha$, from the level flight condition, then there is an increase in wing lift, ΔL_w, which produces a pitching moment about the center of gravity tending to increase the incidence as in *Figure* 3. To counter this, a smaller wing, the horizontal stabilizer, is added far from the center of gravity along the longitudinal axis of the airplane. The increase of incidence also affects the horizontal stabilizer and its lift increases by ΔL_t and produces a larger negative pitching moment more than compensating for the destabilizing effect of the wing. This tends to restore the original equilibrium condition. Thus $\Delta\alpha$ varies with time as in *Figure* 3. It is to be noted that the decay of the oscillations illustrated in the figure is due to aerodynamic damping which will be considered in a later part of this series of articles.

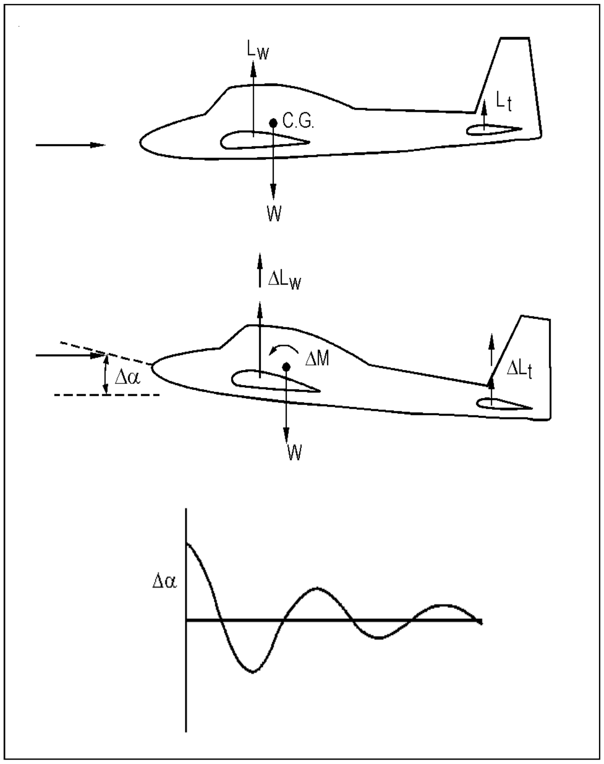

Figure 3. Airplane motion following a small change in incidence.
The disturbance in the form of a small change of incidence alters the aerodynamic forces and moments on the airplane. Thus the equilibrium of forces and moments is affected. The unbalanced forces and moments induce a motion which develops over time. Stability implies the eventual disappearance of this additional motion.

Motions involving yaw and roll, the lateral motions, are more complex and are always coupled. Motion in yaw is stabilized by the vertical stabilizer in a manner similar to the horizontal stabilizer in pitch. A rolling motion cannot be stabilized in this manner as there is no passive device which can do this. Upward tilt of the wings along the span by a small angle, the dihedral angle, helps by inducing a rolling moment due to sideslip (related to yaw) in a favorable manner. This will be considered in a later article.

If an airplane is not stable in the sense defined above, then it will not return to the undisturbed original flight condition following a disturbance. It could diverge from the original condition or the oscillations could build up over time. In these cases, it is possible for the pilot to intervene and try to restore the original flight condition by operating the flight controls. His success in this task will depend on the rapidity with which the departure from the original condition takes place. A human being as a controller has limitations in terms of time duration for perception and action. In general, any departure which takes several seconds to double the amplitude of motion can be successfully controlled. But motions which build up more quickly cannot be thus controlled. The characteristics of the motion of an airplane following a disturbance thus influence the pilot’s feeling of controllability (handling qualities) of the airplane. Desirable handling qualities are specified in terms of frequencies and damping ratios of transient motions following a disturbance and will be considered in a later article.

3.3 *Airplane Control*

In order to perform its mission effectively, an airplane has to be capable of taking off from an airport, climb to cruise altitude, choose its heading by performing turns, cruise at a speed within specified limits, descend and land at a suitable airport. In addition to the above, a combat aircraft may have to perform rapid maneuvers like dives, pull-ups, sharp turns, and rolls. Thus the airplane has to be provided with controls which the pilot can operate to alter the flight path of the airplane. In general, the controls for an airplane alter its flight path by creating aerodynamic moments about its three axes. Thus, deflection of the elevator creates a moment about the OY- or pitch-axis, the rudder about the OZ- or yaw-axis and the ailerons (right and left deflecting in opposite directions) about the OX- or roll-axis. These are called the primary flight controls and are shown in *Figure* 4. In addition, it

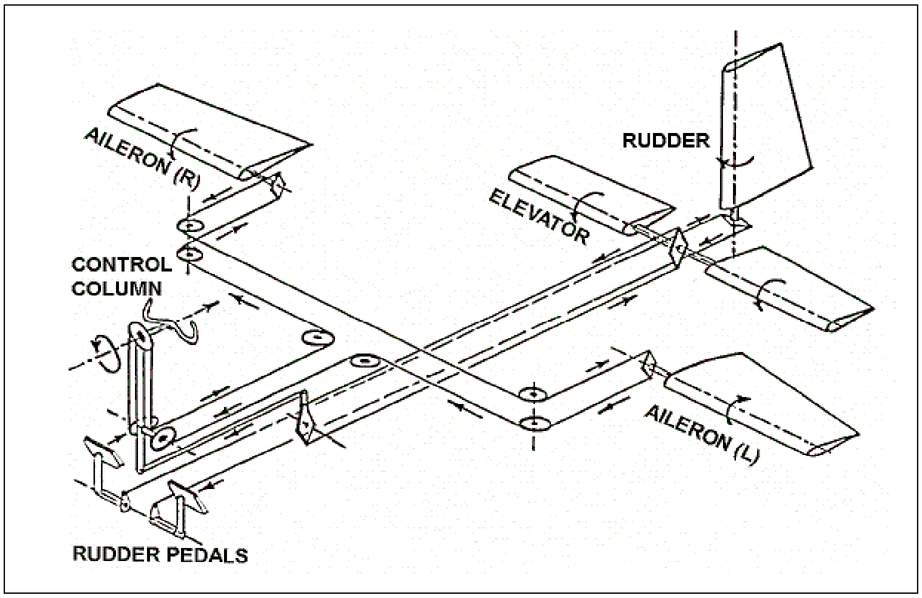

Figure 4. Mechanism for the actuation of control surfaces on an airplane.

The primary flight control surfaces (the ailerons, the rudder and the elevator) are connected to the pilot's controls (the wheel, the pedals and the column) using cables, pulleys and levers. Movement of the control surfaces due to pilot action induces aerodynamic moments about the respective axes of the airplane and hence alters its motion.

is necessary to alter the power or thrust from the propulsion device and this is done by operating a throttle lever. These four controls are generally adequate and all airplanes have these controls.

A tab is a small part of any control surface hinged near its trailing edge. The tab is too small to be of significance in producing forces/moments on the airplane as a whole. However, its deflection in relation to the control surface on which it is located produces a large moment about the hinge of the control surface and thus affects the force felt by the pilot at the control column in manually controlled airplanes. It is useful in such airplanes and depending on its purpose, the tab is named the trim tab, the balance tab or the servo tab.

Besides these, large airplanes generally have flaps for enhancing lift during take-off and landing, nose-wheel steering for easier maneuvering on the ground, wheel brakes for retarding force on the ground, engine-thrust reversers and spoilers for assisting in stopping after landing, speed brakes for rapid reduction of speed in the air and for controlling the rate of descent.

On small airplanes, the primary flight controls are directly operated by the pilot through a mechanical system involving the levers, cables and pulleys as illustrated in *Figure* 4. The pilot's control column moves front and back and deflects the elevator down or up. The control wheel which resembles the steering wheel of a motor car operates the ailerons. The rotation of the wheel produces a moment which is such as to produce the rolling of the wing in the same direction as the wheel. The two pedals operated by the pilot's feet are linked to the rudder. The movement of the right pedal away from the pilot deflects the rudder to the right and produces a positive moment about the OZ-axis (pushing the nose of the aircraft to the right).

On large modern airplanes, there is no direct mechanical connection between the control input devices and the control surfaces of the airplane. The control surfaces are operated by hydraulic servo motors receiving their electrical command signals directly from the control input devices of the pilot or more often from a computer. The computer receives electrical signals from the pilot's input devices (the pilot's commands) as well as from sensors for aircraft motion parameters and control surface positions. The computer, after processing its input information, sends out electrical signals commanding the servos to move as calculated using a control law. The commands are sent digitally at regular intervals of time, typically thirty times a second. Such a system is called a fly-by-wire control system and has many advantages. On combat aircraft, the system relieves the pilot to a great extent so that he can concentrate on other tasks like air combat or weapons delivery. On civil aircraft, it reduces the skill required for flying the airplane and contributes to enhanced safety. It also enhances economy by providing the designer with more freedom for optimally choosing the configuration without worrying about the requirements of manual control and by optimally managing the systems on board (including the engines for balanced thrust and airplane centre of gravity location by scheduling the fuel flow from several tanks). These will be considered in some detail in a later article.

Suggested Reading

[1] G Gabrielli and T Von Karman, What price speed? Specific power required for propulsion, *Mechanical Engineering*, ASME, Vol.72, No.10, pp.775–781, 1950.

[2] Janet Yong, Rod Smith, Linda Hatano and Stuart Hillmansen, What price speed – Revisited, *Ingenia*, Issue 22, Published by the Railway Research Group, Department of Mechanical Engineering, Imperial College of London, March 2005.

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