Chapter 1
Introduction

(Lectures 1, 2 and 3)

Keywords: Definition and importance of flight dynamics; forces acting on an airplane; degrees of freedom for a rigid airplane; subdivisions of flight dynamics; simplified treatment of performance analysis; course outline.

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Chapter 1

Lecture 1

Introduction – 1

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1.1 Opening remarks

At the beginning of the study of any subject, it is helpful to know its definition, scope and special features. It is also useful to know the benefits of the study of the subject, background expected, approach, which also indicates the limitations, and the way the subject is being developed. In this chapter these aspects are dealt with.

1.1.1 Definition and importance of the subject

The normal operation of a civil transport airplane involves take-off, climb to cruise altitude, cruising, descent, loiter and landing (Fig.1.1). In addition, the airplane may also carry out glide (which is descent with power off), turning motion in horizontal and vertical planes and other motions involving accelerations.

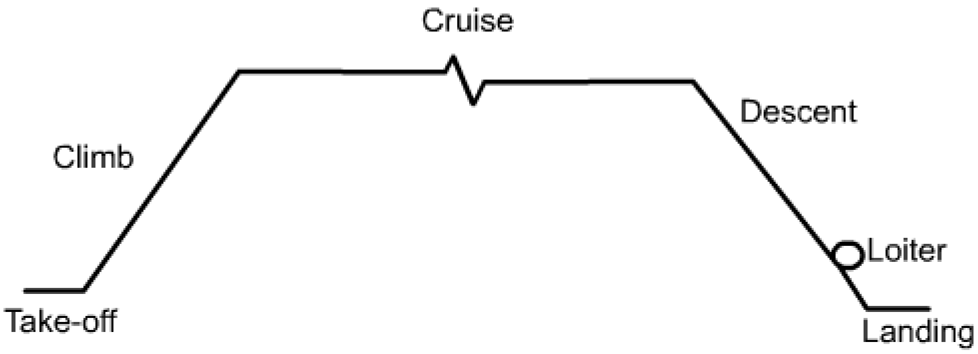

Fig.1.1 Typical flight path of a passenger airplane

Apart from the motion during controlled operations, an airplane may also be subjected to disturbances which may cause changes in its flight path and produce rotations about its axes.

The study of these motions of the airplane – either intended by the pilot or those following a disturbance – forms the subject of Flight dynamics.

Flight dynamics: It is a branch of dynamics dealing with the motion of an object moving in the earth's atmosphere.

The study of flight dynamics will enable us to (a) obtain the performance of the airplane which is described by items like maximum speed, minimum speed, maximum rate of climb, distance covered with a given amount of fuel, radius of turn, take-off distance, landing distance etc., (b) estimate the loads on the airplane, (c) estimate the power required or thrust required for desired performance, (d) determine the stability of the airplane i.e. whether the airplane returns to steady flight conditions after being disturbed and (e) examine the control of the airplane.

Flight dynamics is a basic subject for an aerospace engineer and its knowledge is essential for proper design of an airplane.

Some basic ideas regarding this subject are presented in this chapter. The topics covered herein are listed in the beginning of this chapter.

In this course, attention is focused on the motion of the airplane. Helicopters, rockets and missiles are not covered.

1.1.2 Recapitulation of the names of the major components of the airplane

At this stage it may be helpful to recapitulate the names of the major components of the airplane. Figures 1.2a, b and c show the three-view drawings of three different airplanes.

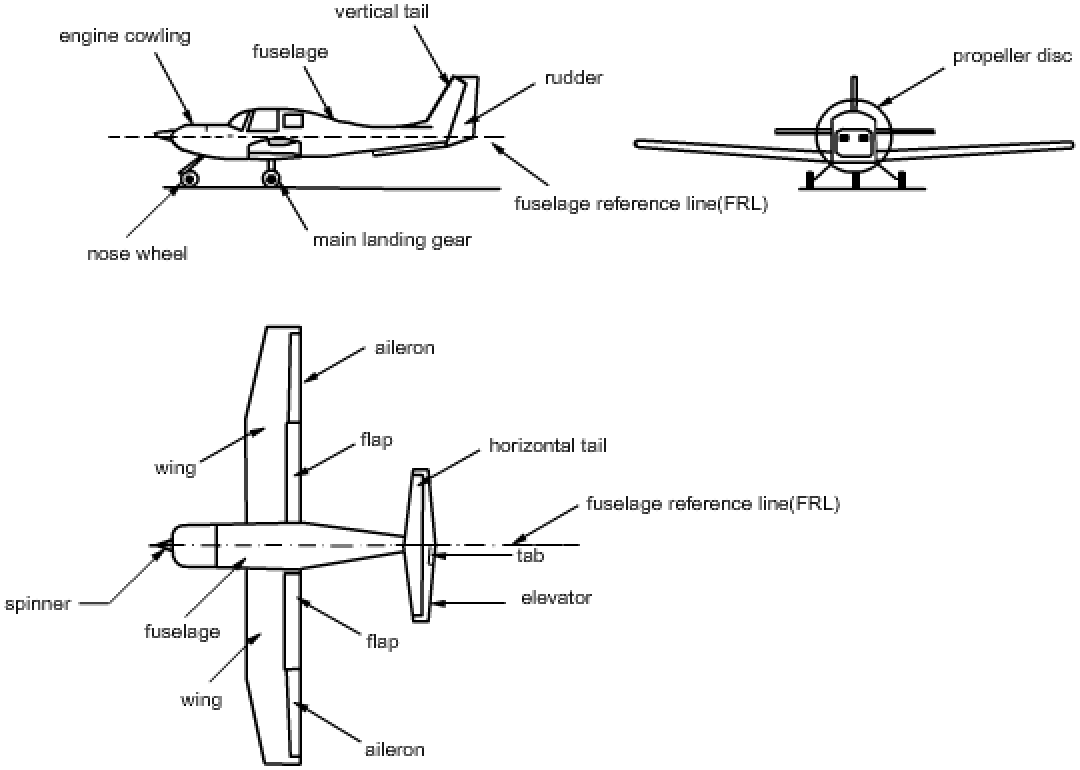

Fig.1.2a Major components of a piston engined airplane
(Based on drawing of HANSA-3 supplied by
National Aerospace Laboratories, Bangalore, India)

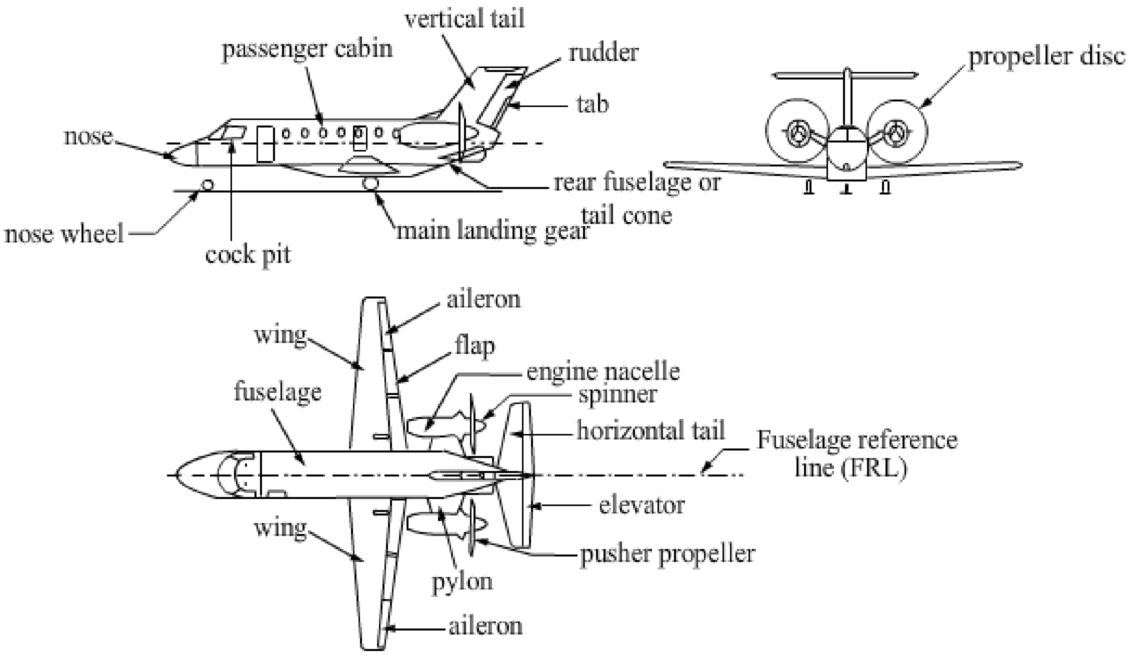

Fig.1.2b Major components of an airplane with turboprop engine

(Based on drawing of SARAS airplane supplied by

National Aerospace Laboratories, Bangalore,India)

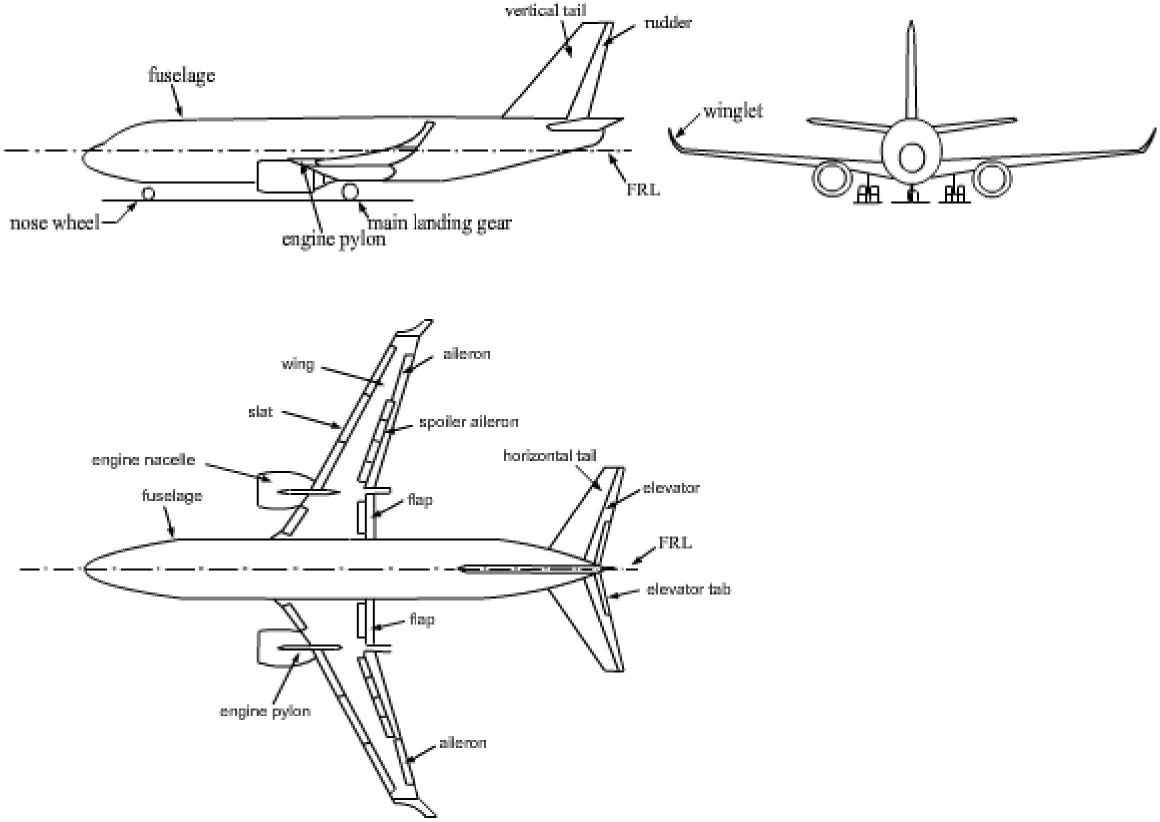

Fig.1.2c Major components of an airplane with jet engine

(Note: The airplane shown has many features, all of which may not be there in a single airplane).

1.1.3 Approach

The approach used in flight mechanics is to apply Newton’s laws to the motion of objects in flight. Let us recall these laws:

Newton’s first law states that every object at rest or in uniform motion continues to be in that state unless acted upon by an external force.

The second law states that the force acting on a body is equal to the time rate of change of its linear momentum.

The third law states that to every action, there is an equal and opposite reaction.

Newton's second law can be written as:

$$\mathbf{F} = m\mathbf{a}\ ;\ \mathbf{a} = d\mathbf{V} / dt\ ;\ \mathbf{V} = d\mathbf{r} / dt \qquad (1.1)$$

Where **F** = sum of all forces acting on the body, m = mass, **a** = acceleration, **V** = velocity, **r** = the position vector of the object and t = time

(**Note:** quantities in bold are vectors).

Acceleration is the rate of change of velocity and velocity is the rate of change of position vector.

To prescribe the position vector, requires a co-ordinate system with reference to which the position vector/displacement is measured.

1.1.4 Forces acting on an airplane

During the analysis of its motion the airplane will be considered as a rigid body. The forces acting on an object in flight are:

- Gravitational force
- Aerodynamic forces and
- Propulsive force.

The gravitational force is the weight (W) of the airplane.

The aerodynamic forces and moments arise due to the motion of the airplane relative to air. Figure 1.3 shows the aerodynamic forces viz. the drag (D), the lift (L) and the side force (Y).

The propulsive force is the thrust(T) produced by the engine or the engine-propeller combination.

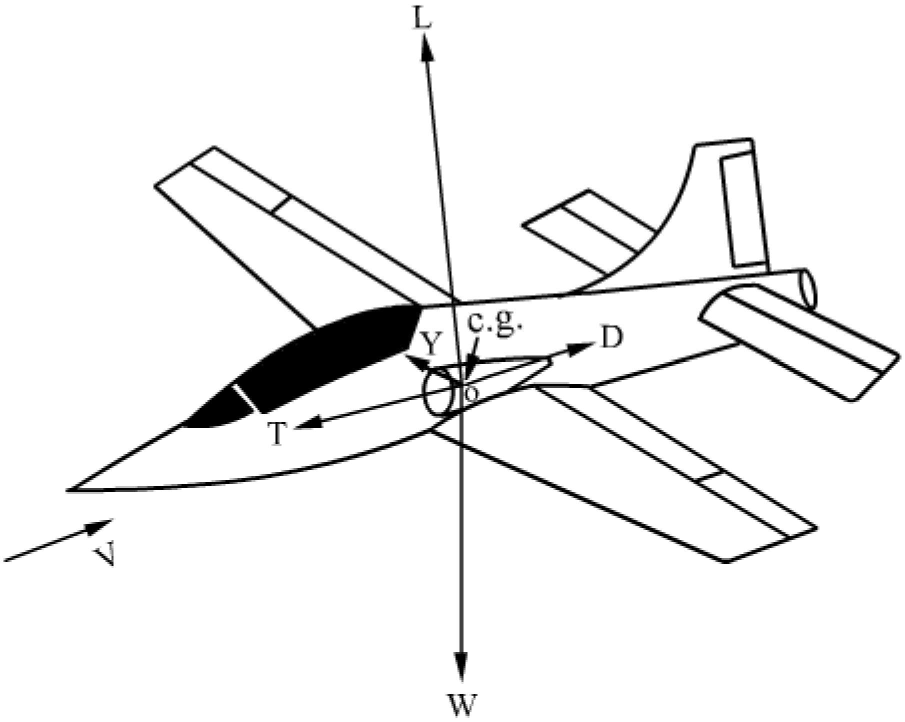

Fig.1.3 Forces on an airplane

1.1.5 Body axes system of an airplane

To formulate and solve a problem in dynamics requires a system of axes. To define such a system it is noted that an airplane is nearly symmetric, in geometry and mass distribution, about a plane which is called the 'Plane of symmetry' (Fig.1.4a). This plane is used for defining the body axes system. Figure 1.4b shows a system of axes ($OX_bY_bZ_b$) fixed on the airplane which moves with the airplane and hence is called 'Body axes system'. The origin 'O' of the body axes system is the center of gravity (c.g.) of the body which, by assumption of symmetry, lies in the plane of symmetry. The axis OX_b is taken positive in the forward direction. The axis OZ_b is perpendicular to OX_b in the plane of symmetry, positive downwards. The axis OY_b is perpendicular to the plane of symmetry such that $OX_bY_bZ_b$ is a right handed system.

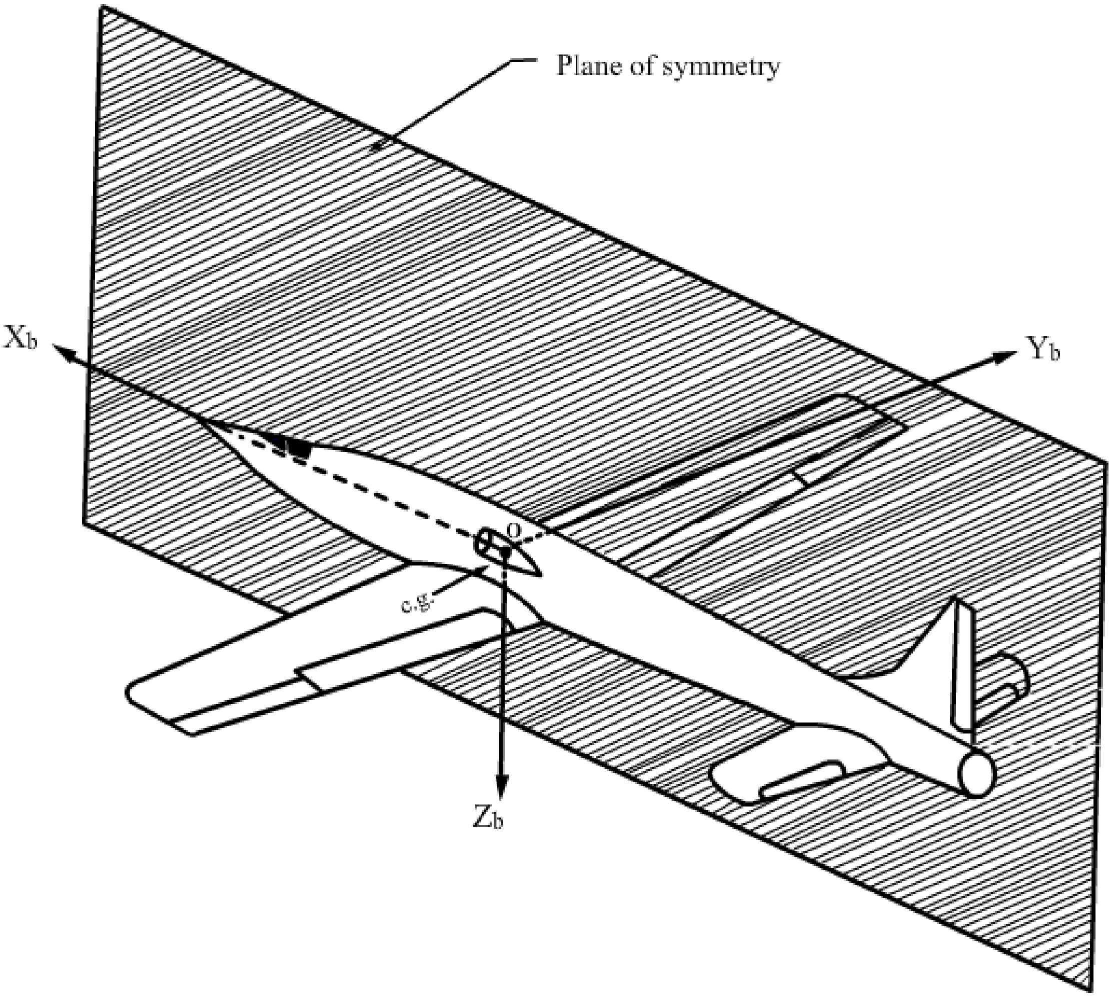

Fig.1.4a Plane of symmetry and body axis system

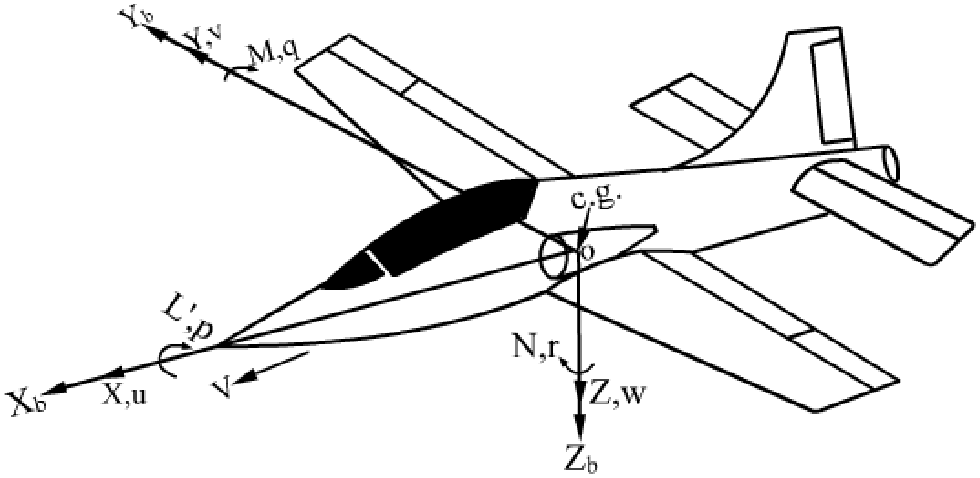

Fig.1.4b The forces and moments acting on an airplane and the components of linear and angular velocities with reference to the body axes system

Figure 1.4b also shows the forces and moments acting on the airplane and the components of linear and angular velocities. The quantity **V** is the velocity vector. The quantities X, Y, Z are the components of the resultant aerodynamic force, along OX_b, OY_b and OZ_b axes respectively. L', M, N are the rolling moment, pitching moment and yawing moment respectively about OX_b, OY_b and OZ_b axes; the rolling moment is denoted by L' to distinguish it from lift (L). u,v,w are respectively the components, along OX_b, OY_b and OZ_b, of the velocity vector (**V**). The angular velocity components are indicated by p, q, and r.

1.1.6 Special features of Flight Dynamics

The features that make flight dynamics a separate subject are:

i)During its motion an airplane in flight, can move along three axes and can rotate about three axes. This is more complicated than the motions of machinery and mechanisms which are restrained by kinematic constraints, or those of land based or water based vehicles which are confined to move on a surface.

ii)The special nature of the forces, like aerodynamic forces, acting on the airplane(Fig.1.3). The magnitude and direction of these forces change with the orientation of the airplane, relative to its flight path.

iii)The system of aerodynamic controls used in flight (aileron, elevator, rudder).

1.2 A note on gravitational force

In the case of an airplane, the gravitational force is mainly due to the attraction of the earth. The magnitude of the gravitational force is the weight of the airplane (in Newtons).

W = m**g**; where **W** is the gravitational force, m is the mass of the airplane and **g** is the acceleration due to gravity.

The line of action of the gravitational force is along the line joining the centre of gravity (c.g.) of the airplane and the center of the earth. It is directed towards the center of earth.

The magnitude of the acceleration due to gravity (g) decreases with increase in altitude (h). It can be calculated based on its value at sea level (g_o), and using the following formula.

$$(g / g_0) = [R / (R + h)]^2 \qquad (1.2)$$

where R is the radius of the earth,

$R = 6400$ km (approx.) and $g_0 = 9.81 ms^{-2}$

However, for typical airplane flights ($h < 20$ km), g is generally taken to be constant.

1.2.1 Flat earth and spherical earth models

In flight mechanics, there are two ways of dealing with the gravitational force, namely the flat earth model and the spherical earth model.

In the flat earth model, the gravitational acceleration is taken to act vertically downwards (Fig 1.5).

When the distance over which the flight takes place is small, the flat earth model is adequate. Reference 1.1, chapter 4 may be referred to for details.

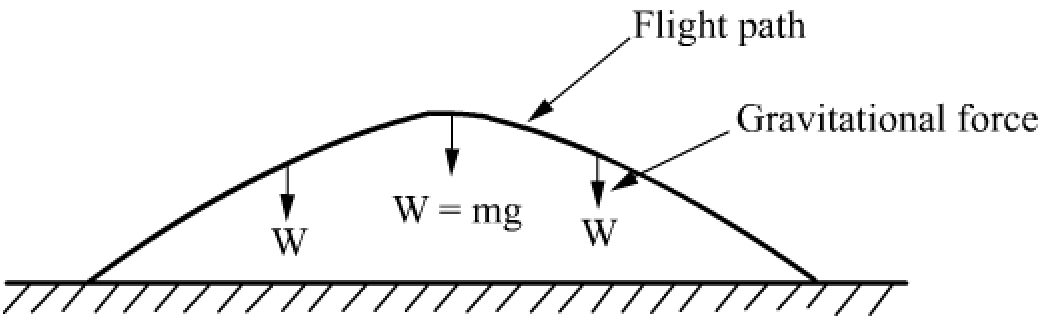

Fig.1.5 Flat earth model

In the spherical earth model, the gravitational force is taken to act along the line joining the center of earth and the c.g. of the airplane. It is directed towards the center of the earth (Fig.1.6).

The spherical earth model is used for accurate analysis of flights involving very long distances.

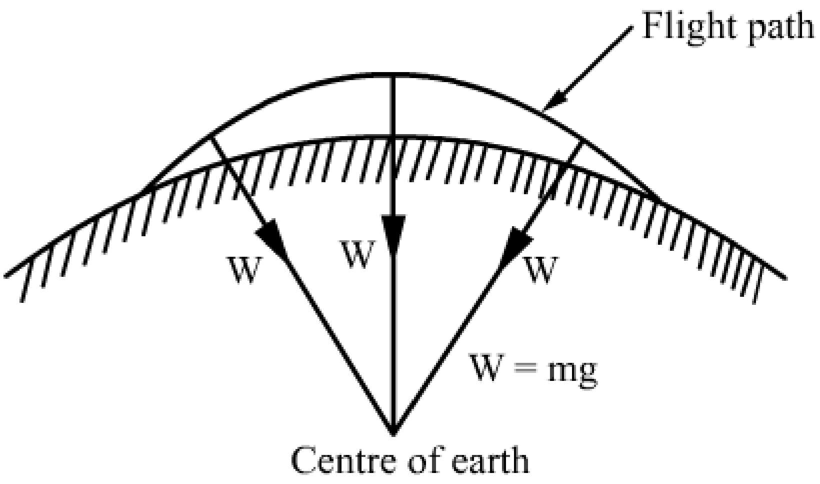

Fig.1.6. Spherical earth model

Remarks:

In this course the flat earth model is used. This is adequate for the following reasons.

i) The distances involved in flights with acceleration are small and the gravitational force can be considered in the vertical direction by proper choice of axes.

ii) In unaccelerated flights like level flight, the forces at the chosen instant of time are considered and the distance covered etc. are obtained by integration. This procedure is accurate as long as it is understood that the altitude means height of the airplane above the surface of the earth and the distance is measured on a sphere of radius equal to the sum of the radius of earth plus the altitude of airplane.

iii) As mentioned in section 1.1.4, the forces acting on the airplane are the gravitational force, the aerodynamic forces and the propulsive force. The first one has been discussed in this section.The discussion on aerodynamic forces will be covered in chapter 3 and that on propulsive force in chapter 4.

1.3 Frame of reference

A frame of reference (coordinate system) in which Newton's laws of motion are valid is known as a Newtonian frame of reference.

Since Newton's laws deal with acceleration, a frame of reference moving with uniform velocity with respect to a Newtonian frame is also a Newtonian frame or inertial frame.

However, if the reference frame is rotating with an angular velocity ($\boldsymbol{\omega}$), then, additional accelerations like centripetal acceleration {$\boldsymbol{\omega} \times (\boldsymbol{\omega} \times \mathbf{r})$} and Coriolis acceleration ($\mathbf{V} \times \boldsymbol{\omega}$) will come into picture.

Reference 1.2,chapter 13 may be referred to for further details on non-Newtonian reference frame.

1.3.1 Frame of reference attached to earth

In flight dynamics, a co-ordinate system attached to the earth is taken to approximate a Newtonian frame (Fig.1.7).

The effects of the rotation of earth around itself and around the sun on this approximation can be estimated as follows.

It is noted that the earth rotates around itself once per day. Hence

$\omega = 2\pi/(3600 \times 24) = 7.27 \times 10^{-5}\ s^{-1}$;

Since r roughly equals 6400 km; the maximum centripetal acceleration ($\omega^2 r$) equals 0.034 ms^{-2}.

The earth also goes around the sun and completes one orbit in approximately 365 days. Hence in this case,

$\omega = 2\pi / (365 \times 3600 \times 24) = 1.99 \times 10^{-7} s^{-1}$;

Further, in this case, the radius would be roughly the mean distance between the sun and the earth which is 1.5×10^{11}m. Consequently, $\omega^2 r = 0.006\ ms^{-2}$.

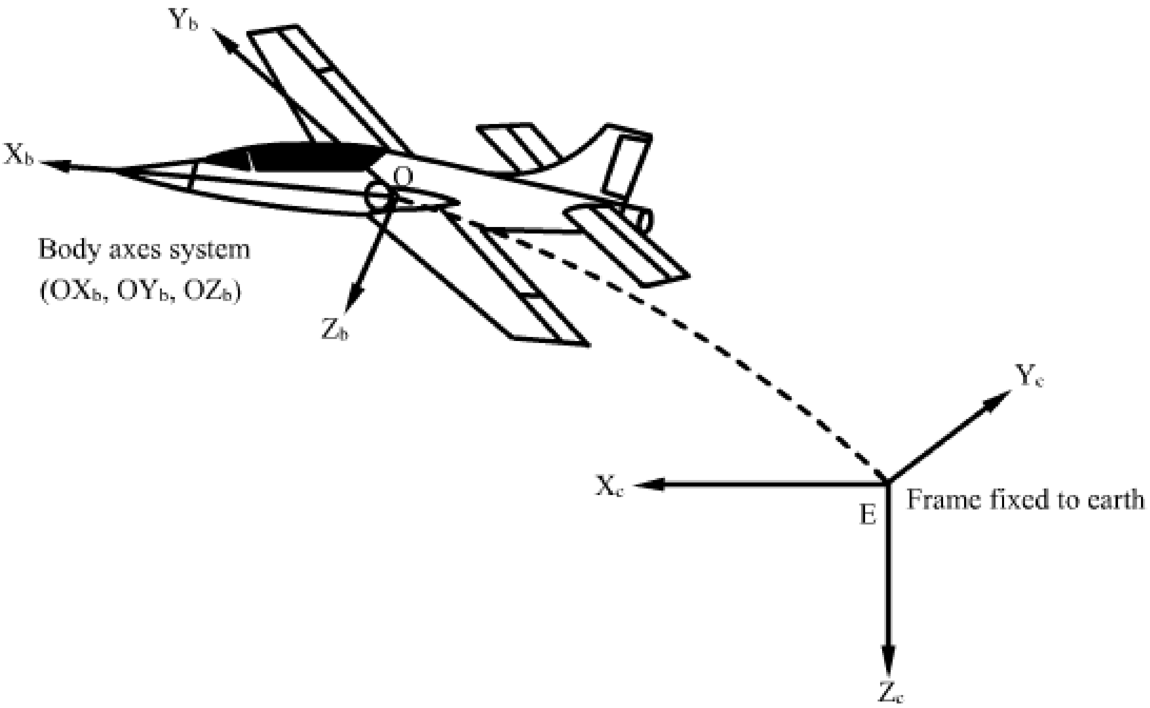

Fig.1.7 Earth fixed and body fixed co-ordinate systems

Thus, it is observed that the centripetal accelerations due to rotation of earth about itself and around the sun are small as compared to the acceleration due to gravity.

These rotational motions would also bring about Coriolis acceleration (**V x ω**). However, its magnitude, which depends on the flight velocity, would be much smaller than the acceleration due to gravity in flights up to Mach number of 3. Hence, the influence can be neglected.

Thus, taking a reference frame attached to the surface of the earth as a Newtonian frame is adequate for the analysis of airplane flight. Figure 1.7 shows such a coordinate system.