

Introduction to Launch Vehicle Analysis and Design

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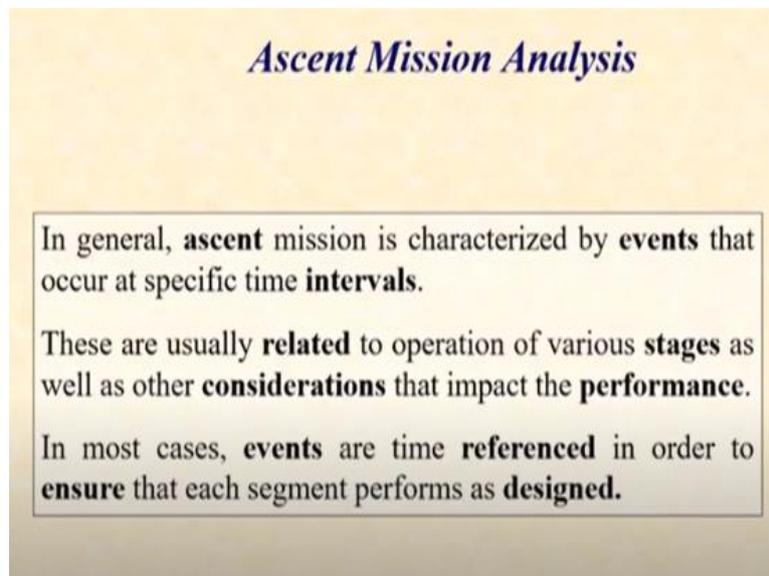
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Lecture - 03

Ascent Mission Basics

Hello and welcome. In this segment we will consider the ascent mission, its definition and some features that will help us understand some of the fundamental aspects of the rocket technology.

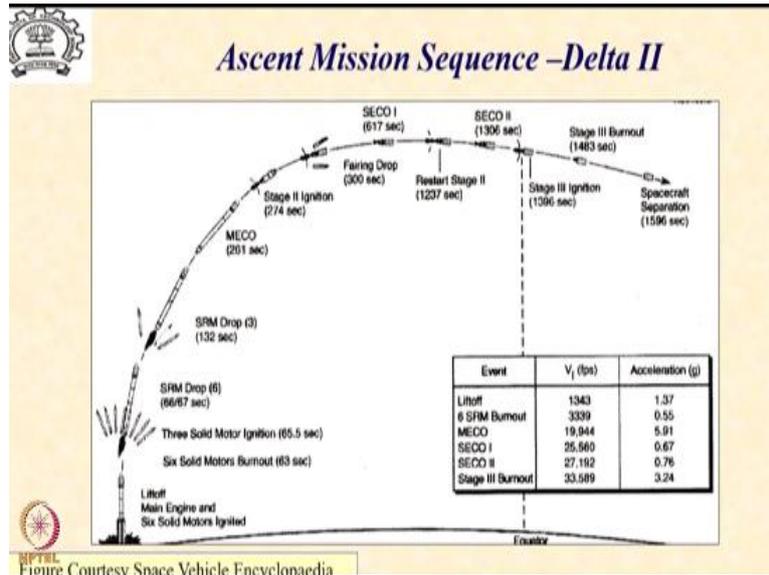
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So let us first try and understand what ascent mission is all about. In general, we will find that ascent mission which is nothing but the task of transporting an object of interest from Earth to a designated spot in space and impart it sufficient energy so that it can carry out the designated tasks. So, this ascent mission is characterized by events that occur at specific time interval.

These are usually related to operation of various stages as well as other considerations that impact the performance. In most cases, the events are time referenced in order to ensure that each segment performs as designed and that there is a way by which you could verify the performance whether it has happened in the specified time.

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So, I want to show you a typical ascent mission sequence that is for a Delta II rocket. The figure is taken courtesy the Space Vehicle Encyclopedia. But what I would like you to look at in this picture is the various events, their sequence and the respective timestamp. So, at the beginning we have the liftoff. Then as we can see, there is a motor burnout with a timestamp of 63 seconds.

If I go to another point, there is a stage II ignition at 274 seconds. There is a stage III ignition at 1396 seconds and then the final the spacecraft separation at 1596 seconds. Also, there is a small table on the bottom right corner, which gives additional information about this particular operation in the form of two additional parameters that is the velocity at each of those locations and the acceleration which the vehicle is undergoing at different time instants.

Now with this you would immediately realize that an ascent mission is a reasonably complex scenario and will require a great amount of effort in analysis and design.

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Ascent Mission Characteristics

We note that **events** are not only time **stamped** but also have **trajectory** information e.g. velocity, altitude, inclination etc., **connected** to it.

Further, as events **denote** changes in **force** system, these have a **mechanics** related implication, as well.

Therefore, it is **possible** to define appropriate **segments** of ascent **mission** that are based on **corresponding** models.

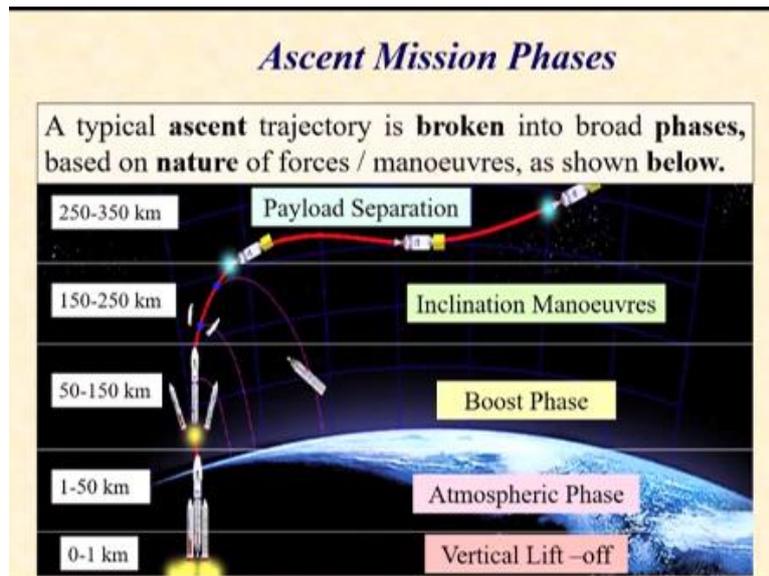
The complexity comes from the fact that there is a certain connection between the trajectory information that is the velocity, altitude, inclination with the time which obviously means that there is a specific trajectory that one needs to achieve. Which means a requirement that a group of parameters which are related trajectory must be achieved at a specific time.

And which obviously means that you must be able to predetermine what that segment should be, so that this particular connection can be established. Another point which is not very clearly seen in this picture, but it is very much there that as the trajectory evolves over a period of time, there are changes in the force system which have a mechanics related implication as well.

Just to give you a perspective, when you are closer to the earth, atmosphere is dense. When you are in the higher atmosphere you have large velocities. So, there is also a change in the way in which the atmosphere will act, the gravity will act. So obviously, you need to appropriately take care of these aspects and ensure that a desired trajectory is realized.

Typically, in the context of ascent mission, it is found useful to create appropriate segments and within each segment, a specific type of model is used, which is applicable for that segment and then these segments are arranged in the correct sequence so that when a mission is performed in that sequence, the desired trajectory is realized.

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To understand this further and also to do this task in a reasonable manner. A typical ascent trajectory is broken into broad phases, which are directly driven by the nature of forces as well as the maneuvers which are required to be performed in those segments, and is shown in the picture below.

So, it is the same picture that we saw earlier, but now we have also introduced the various segments which will involve different force systems and hence different types of mechanics-based models to capture the physics. So very close to earth, you have vertical liftoff. Then from up to 50 km we have the atmospheric phase because typically for all space missions, we assume that beyond 40 odd km the atmosphere possibly will not exist.

And then of course, we have the major boost phase where a large amount of mechanical energy is imparted by burning large amount of propellants. And once the sufficient velocity is acquired, we start performing applicable territory maneuvers and then reach a point where possibly you want to release the payload which is a spacecraft or satellite after which it is assumed that the spacecraft will perform the task as designed or as required.

So, it is with these segments that we are now more concerned. So let us look at these segments in little more detail.

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Lift off & Atmospheric Phase

Lift –off is a critical phase, as **toppling** due to gravity is the **major** issue and is modelled simply as $T > W$, while ensuring vertical **attitude**.

Once **clear** of launch tower, **boosters** and/or first stage **engines** propel the **vehicle** through dense **atmosphere**.

In this phase, while **gravity** & thrust are the **dominant** forces, aerodynamic **drag** is also quite significant.

So let us first look at the liftoff at atmospheric phase and see what are the mechanics related implications of this particular set of phases. So, lift-off is of course, an extremely critical phase particularly because you are having an unstable configuration that you are trying to balance a rocket on its tail and the toppling due to gravity is the major issue.

And from mechanics point of view, it is generally modelled as the thrust which is the forward force greater than the weight, so that it will lift-off and start moving vertically. There is a requirement that you must ensure the vertical latitude during this phase. So once clear of launch tower, boosters and first stage engines propel the vehicle through dense atmosphere. In this phase, it is found that gravity and thrust are the dominant forces.

Aerodynamic drag also becomes significant because atmospheric density is higher even though the velocities may not be very high. Because the density is higher, aerodynamic drag becomes a significant force.

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Boost Phase & Inclination Manoeuvres

In **boost** phase, as the **rocket** is out of **atmosphere**, larger velocity **increments** are possible.

Towards the end of **boost** phase, manoeuvres are carried out to **rotate** the velocity **vector** in order to **achieve** the desired terminal **inclination**.

In these phases, **motion** is assumed to be in **vacuum**, though altitude correction to **gravity** may be needed.

In the next phase, where you have the boost, it means you are out of the atmosphere by a large amount and you are inclining yourself. Of course, once you are out of the atmosphere, larger velocity increments are possible. So, you burn a larger amount of propellant, generate a large amount of thrust, so that you can achieve large accelerations and large velocity increments.

And towards the end of the boost phase maneuvers are carried out to rotate the velocity vector in order to achieve the desired terminal inclination and this is where you will require some kind of maneuver or control over the trajectory. Of course, beyond the 40 or 50 km altitude, generally we assume that the motion is in vacuum even though strictly speaking it is not.

Because there will be some amount of atmospheric density which will continue even though it may not be in the continuum format. There may be dissociation of gases, particularly once you reach about 100 km altitude where you have the ionosphere and you cross it. There are charged particles with great speed which can have some impact.

So, in many realistic cases, up to about 75 km, we still assume that some amount of drag may be quite small, is still applicable for more realistic and accurate solutions. But for initial configuration design, we generally find that beyond 40 km assuming the atmosphere to be absent gives a fairly good estimate of the launch vehicle performance and its trajectory.

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Ascent Mission – Terminal

Terminal phase is considered the **most** crucial as spacecraft **separates** after acquiring required **velocity** / inclination.

In this **phase**, thrust is very **small** so that the motion is **governed** mainly by the gravitational **force**.

However, **distance** travelled over Earth can be very **large**, needing a suitable **Earth** surface geometric model.

Then of course, we reach the terminal phase, is the most crucial as the spacecraft is going to separate from the launch vehicle. So, it is a physical breakage, the connections are broken. So, you must be sure that the initial conditions required for the spacecraft are achieved by the terminal phase and that the separation itself is a team operation. Of course, in this phase, the thrust is really very small.

And the only force, which is going to have a mechanics implication is the gravitational force. But then in this phase as you would see in both the pictures that we have introduced, the distance traveled over Earth can be very large. And that now you may need to bring in a suitable geometric model for Earth surface for modeling the kinematics and the associated dynamics.

So, as you would have noted, as the spacecraft is released at the end it will obviously operate in vacuum. But for the launch vehicle right from the liftoff to the injection point, in different segments different force systems are applicable. And hence, you also need to appropriately look at the mathematical models which are applicable in each of those segments.

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Ascent Mission Modelling

And that brings us to this important idea of ascent mission modeling. Let us look at how we are going to capture this so that we can achieve the objective of the trajectory and also achieve the configuration of a rocket which will make it happen.

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Ascent Mission Modelling

Modelling of the ascent mission involves, (1) identifying the applicable **forces**, (2) desired motion **parameters** and (3) the physical **laws**, governing the motion.

As we have seen, **launch** vehicle experiences **forces** due to **propellant** burning, gravity and **atmosphere**.

Similarly, **motion** variables of interest are **position** and velocity vectors of the **centre of mass** (or velocity, altitude and flight path angle).

So, this whole process of modeling of ascent mission involves three components. The first we need to identify the applicable forces in that segment. Then we need to identify the desired motion parameters that are of interest from the trajectory perspective and the physical laws which are going to govern the motion in that segment.

While there can be many forces as we have seen in the preceding discussion, typically forces due to propellant burning, gravity and atmosphere are going to dominate the motion and the trajectory of the launch vehicle. Further, we will find that the motion

variables of interest are position and velocity vectors of the center of mass which sometime are split into the velocity, the altitude and the flight path angle with respect to a suitable frame of reference.

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Basic Governing Equation

In **inertial** frame, equation of **motion** for the centre of **mass** can be written using **Newton's 2nd** law as,

$$\frac{d}{dt} \{m\vec{V}\} = \vec{F}; \quad \vec{x} = \int \vec{V} dt$$

So let us now introduce the idea of basic governing equations of motion for the launch vehicle as it moves through the atmosphere from liftoff to the terminal point. Of course, to do that, let us first go back to our Newton's law and formulate the equation of motion of center of mass in an inertial frame, which all of us know can be written as follows. This is the statement of Newton's second law that rate of change of momentum is force.

Extremely simple representation and it is of course, written in the vectorial form with arrow at the top of the variables where the position vector \vec{x} is nothing but the integral of the velocity vector and is the corresponding kinematic equation.

So, the first is the dynamic equation, the second one is the kinematic equation, which means in order for us to generate the information for position vector and the velocity vector we must have the force vector and we must solve this first order vector differential equation. So, the first step would be to define force system so that we can solve the first order vector differential equations which are the velocity vector.

And then use the velocity vector to generate the position vector. So, this is the basic requirement from the mechanics perspective as far as this particular exercise is concerned.

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Basic Governing Equation

Here, the inertial **velocity** vector is expressed as,

$$\vec{V} = \vec{V}_0 + \vec{V}_b + \vec{\Omega}_0 \times \vec{R}_b; \quad \vec{V}_0 \rightarrow \text{Velocity of Origin}$$
$$\vec{\Omega}_0 \rightarrow \text{Frame Rotational Velocity}$$
$$\vec{R}_b, \vec{V}_b \rightarrow \text{Relative Position, Velocity}$$

In the context of **ascent** missions, launch point is commonly **taken** as origin of a suitable reference **frame**.

Now how are we going to express the velocity vector? So let us look at the elements of the velocity vector. And we realize that this is not a very simple expression. Of course, we have not yet introduced a coordinate system, but assuming that there is a coordinate system, which is referenced to another inertial coordinate system that V_0 represents the velocity of the origin of the chosen coordinate system in relation to the inertial coordinate system.

V_b is the velocity of the vehicle in the chosen coordinate system. And Ω represents the rotational velocity of the chosen coordinate system. And R_b represents the position of the vehicle in the chosen rotating frame of reference. So, we realize that in a general context, the expression for V would contain all these three terms.

Of course, with certain simplifications and assumptions, we might be in a position to also simplify the expression for velocity, but that we will see when we start looking at some other details. Of course, it is just mentioned at this stage that for most launch missions, the launch point is commonly taken as the origin of a suitable reference frame so that it becomes easier from the interpretation of the trajectory point of view.

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Choice of Coordinate Axes

Further, generally **Cartesian** (i.e. X, Y & Z) coordinate **axes** are used to represent forces and motion variables.

However, in cases where **motion** is confined to a **plane**, either polar **(R, θ)** coordinates or **curvilinear** (s, n) coordinates are also **employed**.

Next let us look at the choice of coordinate axes. In general, we find that the Cartesian coordinate system that is X, Y and Z are convenient, but also used to represent forces and motion variables. However, in cases where motion is confined to a plane, which will happen in most of the ascent missions, we can either use X, Y or polar coordinates R, θ or even curvilinear coordinates s and n to represent the motion of the rocket, center of mass starting from liftoff to its terminal point.

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Ascent Mission Force Models

Ascent mission starts from **earth's** surface and ends at a **pre-fixed** point where **payload** is released.

Further, **motion** profile is generally highly **curvilinear**.

And then, the third point about the mathematical model are the forces. So, ascent mission starts from earth's surface and ends at a pre-fixed point where payload is released. Of course, we have already seen from our earlier two conceptual pictures, that the motion profile is generally highly curvilinear.

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Ascent Mission Force Models

In addition, launch vehicle **accelerates** through propulsive **forces**, in the presence of **gravity** & aerodynamic **forces**.

Thus, we need **models** for gravity, propulsive and **aerodynamic** forces, to setup the governing **equations**.

Of course, we have also noted the fact that the launch vehicle is going to experience large accelerations, because of the propulsive forces and will also be acted upon by the gravity and the aerodynamic forces. Thus, we need accurate mathematical models for gravity, propulsive and aerodynamic forces to set up the governing equations.

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Summary

Ascent mission, while **composed** of time-sequenced **events**, can be defined in terms of **trajectory** segments based on the **nature** of forces and motion.

Newton's law is employed to **formulate** equations in the **coordinate** system that is **located** on the launch site.

Forces that influence the **ascent** trajectory are propulsive, gravitational and **aerodynamic**.

So, to summarize, ascent mission, while composed of time-sequenced events can be defined in terms of trajectory segments based on nature of forces and motion. Newton's law is employed to formulate equations in the coordinate system that is located at the launch site. And finally, we also note that forces that influence the ascent trajectory are propulsive, gravitational and aerodynamic in nature.

With that, we conclude our discussion on the basic features and philosophy of an ascent mission from a mechanics perspective. We will now look at each of those elements one by one and the first element that we will look at will be how to synthesize the forces so that we can solve the first order differential equation to generate the velocity vector. So, with that we will close this segment and we will again meet in the next segment. Till then bye and thank you.