Introduction to Launch Vehicle Analysis and Design

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Lecture – 14
Ascent Mission Design

Hello and welcome. Till now as you would have noticed we have understood the various techniques for generating the ascent mission trajectory and we have also looked at the connection between the trajectory and the burn profile. As we would also realize the burn profile is directly related to the configuration of the launch vehicle in terms of the propellant, the masses.

So, it is now right time to make a connection between the trajectory parameters and the overall rocket configuration which is what we will now look at in this lecture. So, let us begin.

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In this context, let us first look at the connection between the trajectory parameters and rocket design.

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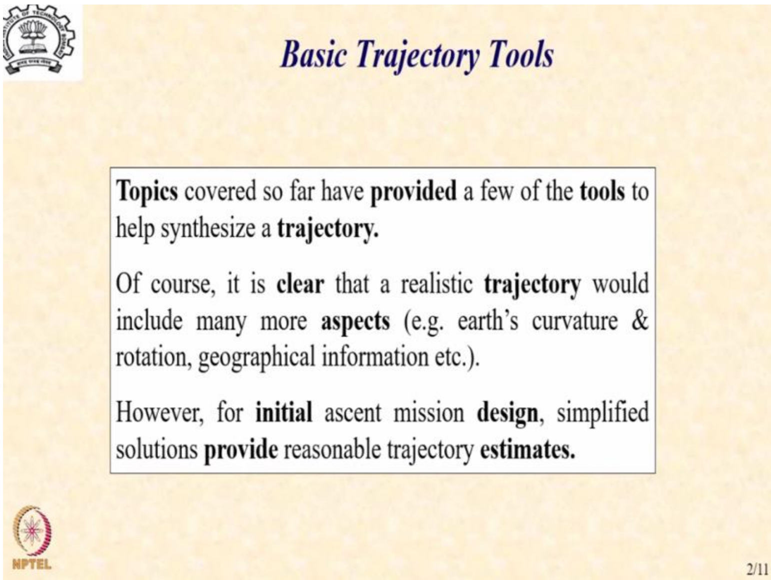

So, in this regard we note that topics covered so far have provided a few of the tools to help synthesize a trajectory. Of course, we are also aware of this fact that a realistic trajectory would include many more aspects such as earth's curvature and rotation, geographical information etcetera. However, for initial ascent mission design, the simplified solutions that we have discussed so far are capable of providing reasonable trajectory estimates.

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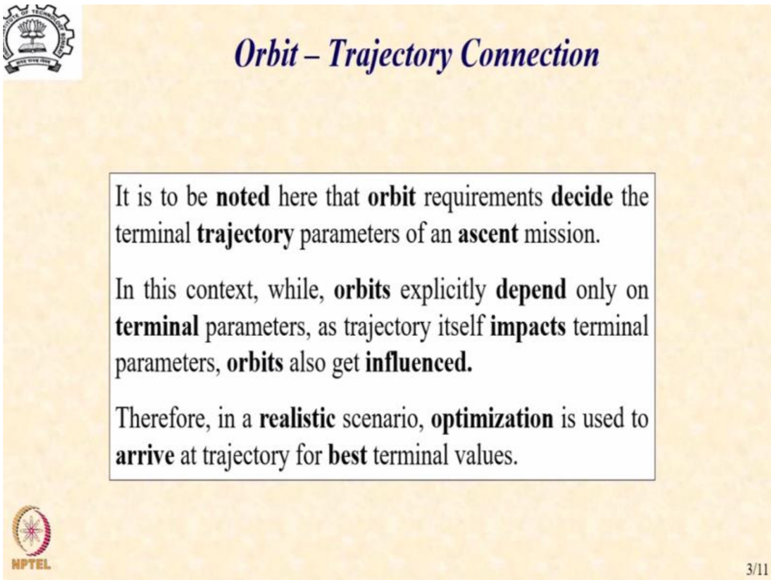

Let us now bring in another dimension to the launch vehicle configuration in the form of orbit trajectory connection. So, in this regard we first need to note that orbit requirements which are essentially related to a space craft mission decide the terminal trajectory parameters of an ascent mission which means that whatever is expected at the end of the burnout or the terminal point is essentially related to what you want from the space craft orbital mission.

Of course, we need to understand that orbits explicitly depend only on the terminal parameters. So, they really have no connection with the remaining part of the trajectory as long as the terminal parameters are as per requirement. However, because of the fact that the terminal parameters are strongly and closely related to the trajectory itself the overall trajectory also is influenced by the orbital mission.

So, generally there is a close coupling between the orbital mission and the trajectory that a launch vehicle will take during its ascent mission. You will find this connection in almost all the launch vehicles of the world. Of course, what we have done so far is a kind of an ad hoc way in which we are arriving at the trajectory, but in realistic context formal and rigorous optimization techniques are used to arrive at a trajectory for best possible terminal values as per the orbital requirement which means that given an orbital mission you arrive at the terminal parameters.

And then try to optimize the ascent mission in such a manner that those required terminal values are achieved in an optimal and most efficient manner.

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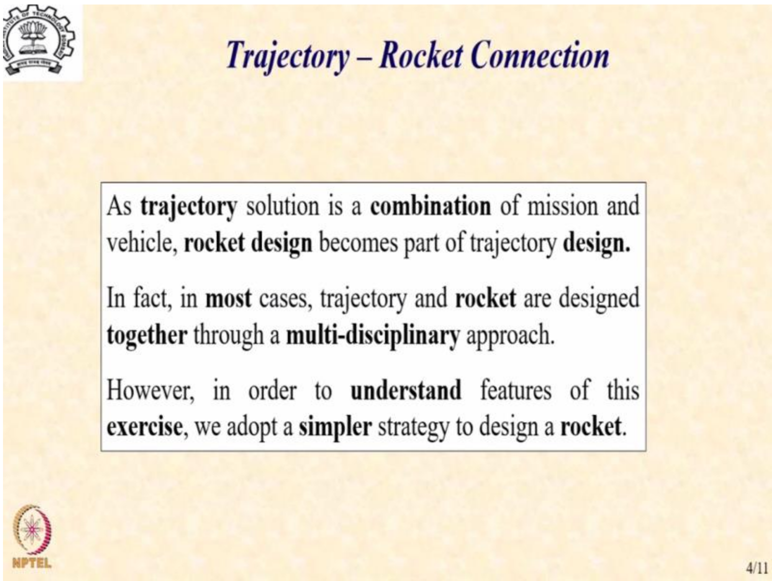

Once we accept this idea that we are going to require a trajectory which requires an optimal perspective because the trajectory is also closely related to the rocket of the launch vehicle itself, we can see that there is also going to be a certain amount of requirement which is going to come on the rocket configuration itself. And as you will see the rocket design becomes an integral part of the trajectory design problem itself that you need to design a rocket that will achieve an optimal trajectory.

That will achieve the desired terminal parameters which in turn will achieve the orbit that is desired by the space craft mission. So, this is the chain of connectivity that we normally need to keep in mind. In fact, you will realize and when you read additional material on this subject that typically rockets and the trajectory are designed together through a multidisciplinary design approach.

However, in the present course we will adopt a simpler strategy which will still help us to design an optimal rocket along with an optimal trajectory, but will be computationally not very intensive so that we can do parametric studies and understand important features of such an exercise which is commonly carried out in the context of most launch vehicles.

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So, let us now turn ourselves to the basic issues involved with design of rocket configuration.

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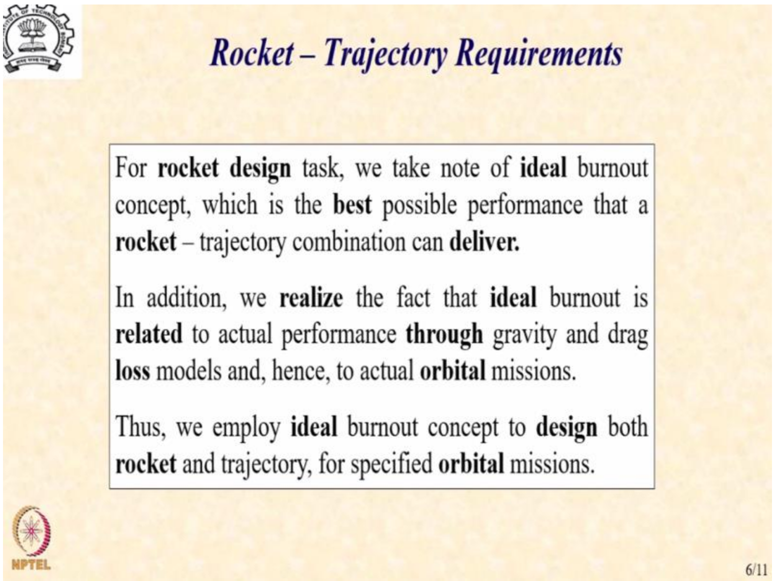

Now, for rocket design task one simplification that we introduce is to bring in the ideal burnout concept which is the best possible performance that a rocket trajectory combination can deliver which means that the ideal burnout is the maximum possible mechanical energy that you can impart from a given rocket. So, if I turn this argument other way round to say that the best possible mechanical energy performance will directly impact the configuration of rocket.

Then now I have a means by which I can arrive at a rocket configuration that will give me the best possible desired performance with least amount of cost and that is where the optimization kicks in. Of course, it is not very difficult to see the connection that the ideal burnout is also related to the actual performance which is dependent on the loss due to gravity and the drag.

So, if we can make a reasonable estimate of these losses, we actually will get the desired actual performance against the designed ideal performance. What it means is that we can actually use ideal burnout which is obtained by compensating for the losses which are likely to occur due to gravity and drag on to the actual desired performance and design the rocket for the ideal performance, the implication is clear.

That, if we design the rocket to achieve the ideal performance then obviously that rocket will also achieve the actual performance as long as we have estimated the losses with reasonable degree of certainty.

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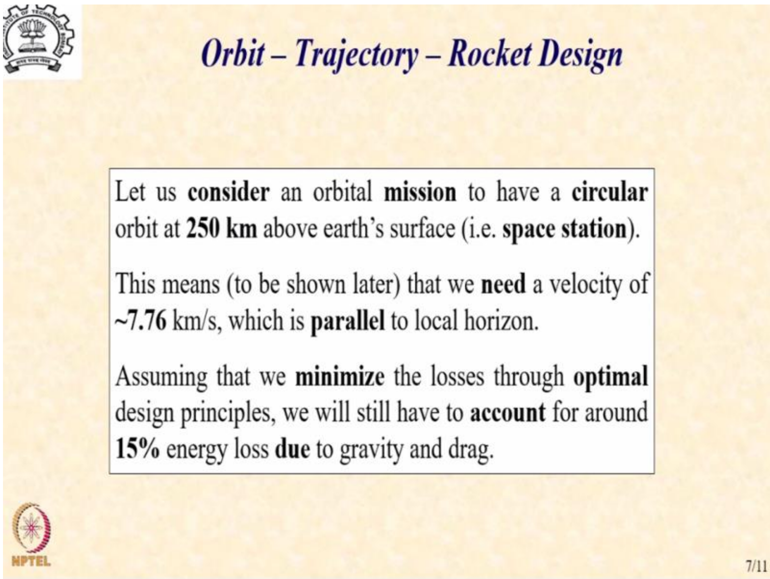

Let me demonstrate this idea through a simple strategy. So, let us begin the orbit trajectory rocket design philosophy as follows. So, let us consider an orbital mission which requires that a space craft is put in a circular orbit at 250 kilometers altitude above the surface of the earth. For example, this could typically be a space station mission which is orbiting in a circular orbit roughly around this altitude.

So, any other mission which is going to space station will have this objective. This means of course this is particular part which is related to the orbital mission which you are not doing, but you can take it from me that in order to do this we will require an actual velocity of 7,760 kilometers per second which is parallel to local horizon at an altitude of 250 kilometers which means we need to impart a mechanical energy which corresponds to a potential energy related to the altitude of 250 kilometers.

And a kinetic energy corresponding to 7.76 kilometers per second which means we now have an estimate of actual mechanical energy required at that terminal point. Now, let us also bring in this idea that we are going to make use of rigorous optimization technique which we will try and minimize our drag and gravity losses and over and above because you are going to make use of gravity turn trajectory.

The gravity losses also will become significantly lower in relation to the vertical motion and solution that we have seen so far. It is reasonable to expect that we can probably bring down all the losses to roughly around 15% of total energy due to gravity and drag which means that if we were to plan for an ideal performance that ideal performance should have two components and energy corresponding to an altitude of 250 kilometer and a velocity of 7.76 kilometers per second and should have a 15% buffer for the loss due to gravity and drag.

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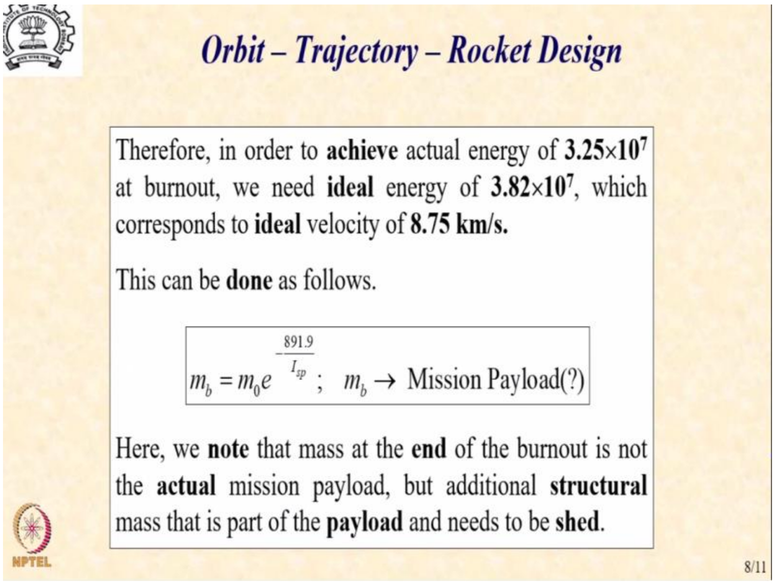

If we put these together, we find that in order to achieve the actual energy of 3.25 into 10 to the power 7 per unit burnout mass please note it's for unit burnout mass. We need ideal energy which is 15% to 20% higher than this. So, it is a 3.82 into 10 to the power 7. Now from our understanding of the ideal burnout we can immediately convert this energy as $\frac{1}{2}V^2$ into the velocity which is ideal.

And it means that if we plan for an ideal velocity of 8.75 kilometers per second. So, which means that if we achieve ideal velocity equal to 8.75 kilometers per second taking into the account the gravity and the drag loss, we will achieve the 7.76 kilometers per second at 250 kilometers altitude which means if we do this, we know that our orbital mission will be feasible.

Now let us go back to our simplified exponential equation that we have seen in the beginning of the discussion on the trajectory where we talked about the ideal burnout performance. So, we know that our burnout mass is related to the lift off mass with this exponential function which contains the ideal burnout velocity. So, now I substitute this 8.75 ideal burnout velocity and now with that I have three quantities that need some decision.

One is the I_{sp} the propellant other one the lift off mass m_0 and m_b is the burnout mass. And here now for the first time we need to raise this flag is this the mission payload. Let me now correct this idea that the final m_b that you are going to get through this equation is not really the actual mission payload, but also contains additional structural mass that is going to be part of the space craft, part of the module which is kept the shell so many things will be there.

And all this will need to be removed before we can say what is going to be our actual space craft mass which will be finally the mass which is going to be of use to us, but from this equation we get a fairly good idea of what is the combined mass which you are going to get if you start with a particular lift off mass and an I_{sp} along with a propellant. So, it tells you that if you start from some m_0 tons of lift off mass.

Then to achieve this velocity you can afford to have only so much of unburnt mass at the end which means the remaining all has to be propellant which means indirectly this equation is now giving you a requirement on the propellant for a specific lift off mass and I_{sp}. And this is now a domain in which you now have to worry about the rocket configuration which will involve for propellant to use and how much of it to use.

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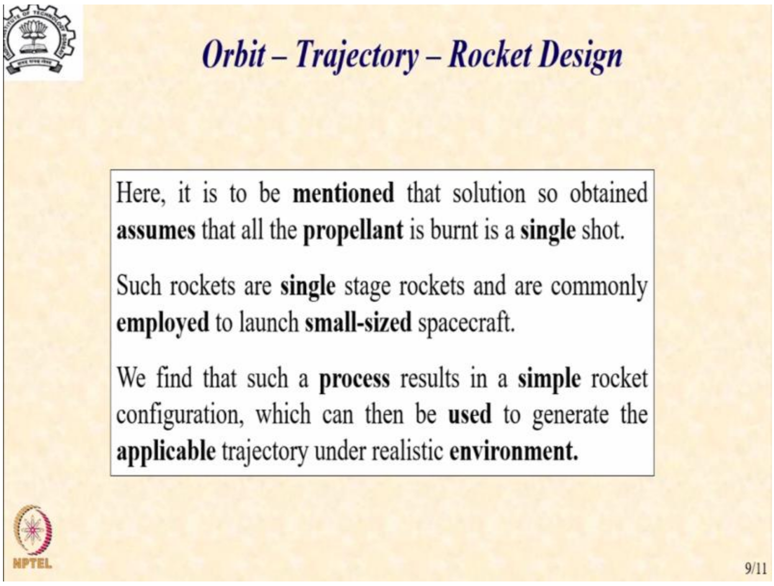

But there is another aspect that we now need to bring in before the solution becomes kind of complete. The equation that we have seen previously assumes that once you start burning the propellant you do not stop until all the propellant is consumed or that you are burning the propellant in a single shot. Such rockets are called single stage rockets and are commonly employed to launch small size space craft.

In fact, all the sounding rockets are typically single stage rockets that they burn all the propellant in one shot at the end of which whatever is the payload that they are carrying is released and that becomes the end of the mission. Of course, we realize immediately that such an operational aspect of mission will result in a very, very simple rocket configuration that you pack in all the propellant, ignite it, put all your controls in place and leave it.

In fact, this is a very interesting and very practical concept that is commonly used in the context of missiles where the concept is typically called fire-and-forget that you just ignite and forget, the object will take care of itself and it really works can be used in realistic environment.

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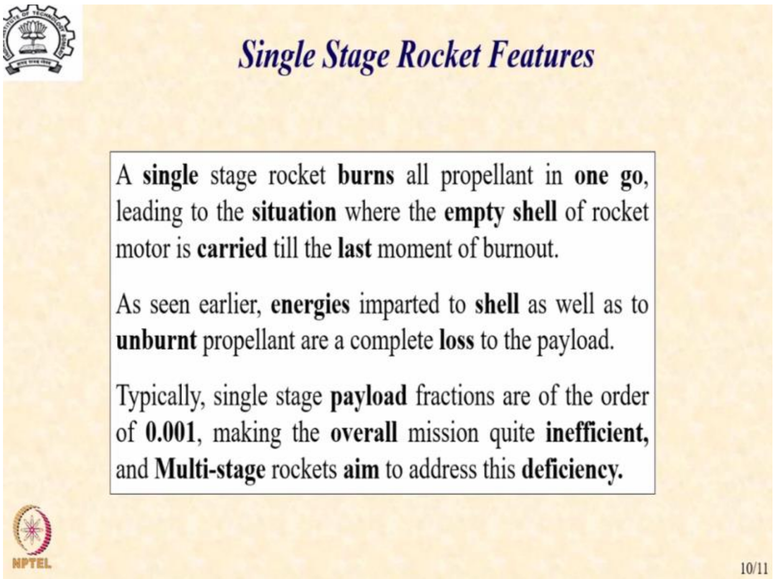

But there are certain issues that we now need to look at this particular mode of operation. The fact that a single stage rocket is going to burn all propellant in one go the empty shell which you started off with right from the beginning continues with you right till the end and that mass you are accelerating and imparting the same kinetic energy which is not going to be of any use to you because the actual space craft or a payload is going to be a very small amount of or a fraction of this which obviously means that this particular mode of operation is highly inefficient from energy point of view.

So, obviously your losses are going to be significantly high. One way of mitigating this loss is to make the shell as thin as possible, reduce this structural mass as much as possible and that is an area of research in which optimal structural designs are being practiced where you tried to use the structural mass to an absolute minimum which is possible for the mission to take place.

But then there is still a limit to what you can go. So, is there any other way that we can make the mission even more efficient and not have the drawback. The reason why this issue is important is that typically when you look at a single stage operation of rockets like what we have been discussing typically the payload fraction which is an important figure of merit of any ascent mission which is nothing, but the ratio of the final payload to the lift off mass.

That is payload in kg per unit kg of lift off mass it is of the order of 0.001 or 0.1% which means that if you want to launch one kg of payload you will need to have a rocket which will be of the mass 1,000 kg and that is the point which directly impacts the overall cost of launch in an ascent mission. So, obviously you would like this number to be significantly higher than this and, in this context, now I will introduce the idea of multi stage rockets which aim to directly address efficiency.

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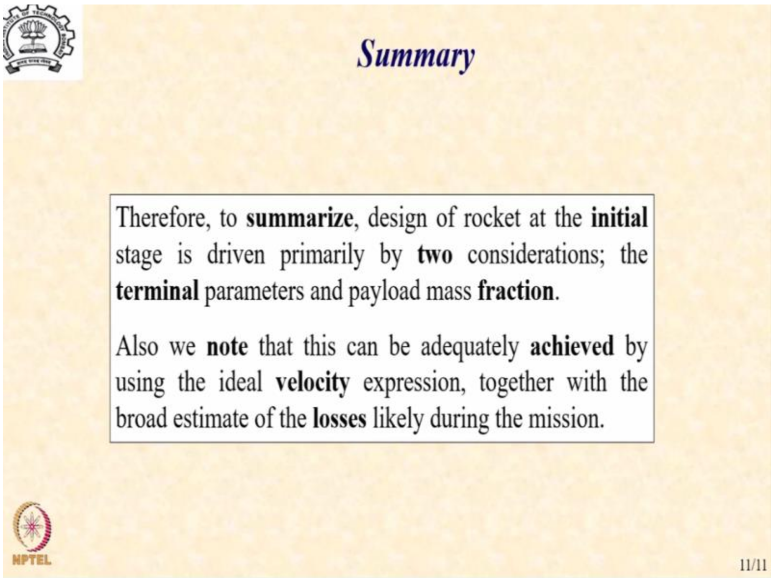

Therefore, to summarize design of rocket at the initial stage is driven primarily by two considerations, the terminal parameters and the payload mass fraction. Also, we note that this can be adequately achieved by using the ideal velocity expression together with the broad estimate of the losses likely during the mission. So, we have seen that while single stage operations are simple configurations of rockets that achieve the desired terminal velocity.

They are not very efficient from payload fraction point of view and hence we need to look at an alternate way in which we can improve significantly the efficiency of efficient and in that context, we will now be looking at the multi stage concept for rockets in the next lecture. So, bye see you in the next lecture and thank you.