Introduction to Launch Vehicle Analysis and Design

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Lecture – 15

Multi-stage Rocket Basics

Hello and welcome. In this lecture, we will establish some of the basic concepts of what multi-staging and rocket is all about. And also understand the kind of benefits that we can derive by creating a multistage rocket for the mission that we have in mind. So, let us begin. So, let us start the discussion by looking at the basic concept itself.

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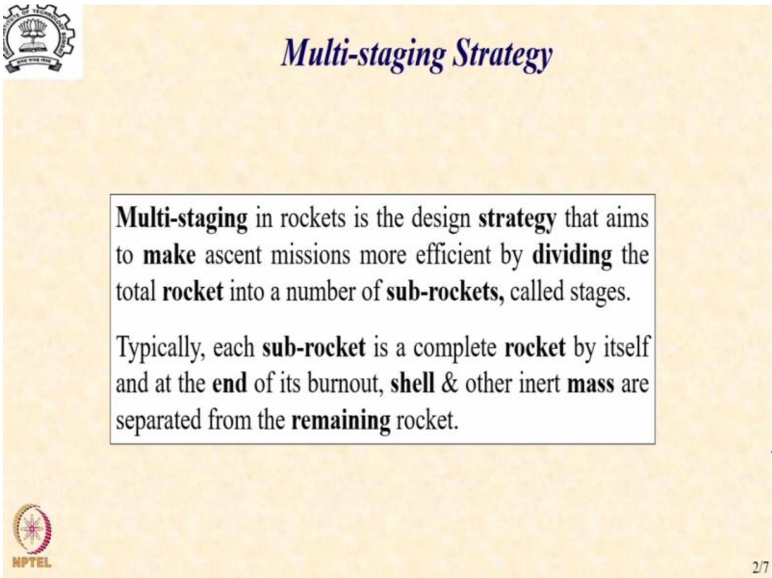

So, multi-staging in rockets is the design strategy that aims to make ascent missions more efficient by dividing the total rocket into a number of sub-rockets called stages. Typically, each sub-rocket is a complete rocket by itself and at the end of the burnout of the sub-rocket, shell and other inert mass are separated from the remaining rocket. This is the fundamental idea of the staging that you divide the total rocket into smaller segments.

And each segment after it finishes the operation is removed from the main body of the rocket and we immediately realize that this would reduce the overall mass of the rocket which will be required for operating the next stage.

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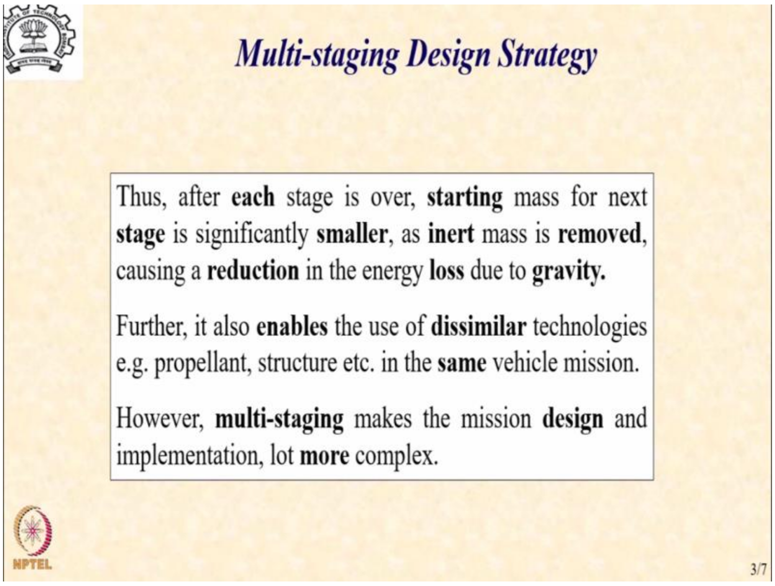

We see that the starting mass now for the next stage is significantly smaller as the inert mass which we were carrying earlier we are no longer carrying and we are throwing it away and this obviously means that the remaining propellant which is in the other stages which have not yet operated will need to accelerate a smaller mass and hence they will become more efficient from the overall loss point of view.

There is a side benefit that we automatically get by dividing the rocket into segments and that is in terms of using different technologies for different segment because each rocket is a unit by itself that unit can be treated separately. And it did not have any commonality with the other units which mean it can use a different propellant like solid or liquid, it can use a different structure like metal, composite, frame structure, honeycomb.

And in the process make the operation of each stage also more efficient and optimal. So, not only the overall rockets become more efficient it is possible for us to also individually make each stage more efficient. Of course, there is always a flip side that the multi-staging makes the mission design, its implementation in terms of fabrication assembly and its operation in terms of the process that help in getting rid of the inert mass a lot more complex configuration.

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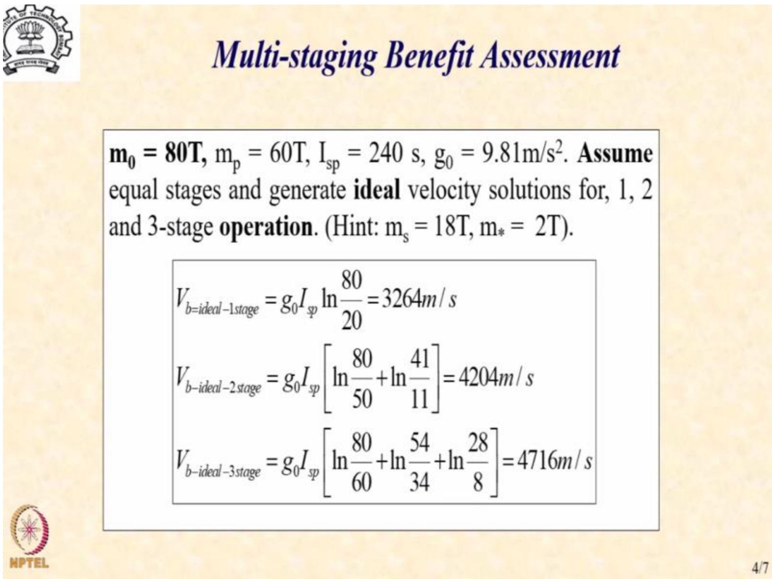

Let us before going through the actual formulation for this kind of a configuration make a quick assessment of what are we likely to get out of this so that we can decide whether it is worth making the effort or not. So, let us take the same problem of a rocket with 80 ton lift off mass carrying 60 ton of propellant having I_{sp} of 240 s. And let us now try and see whether the philosophy that we have just now discussed can be worked on this to understand what kind of performance are we likely to get.

So, here let us make certain assumptions. Let us assume that I am going to divide rocket equally which means if I divide the rocket into two segments each segment will contain 30 tons of propellant and 9 tons of inert mass. And if I divide this into three equal stages, each stage will contain 20 tons of propellant and 6 tons of inert mass. And let us now use the simplified ideal burnout velocity expression just to understand how it gets impacted by performing this particular split.

So, let us first look at the first stage or one stage operation. In one stage operation, I am burning all the 60 tons in a single shot so that at the end all the 18 tons of inert mass is attached to the 2 tons of propellant that is payload mass and we have already seen that we get $3{,}264$ m/s velocity. Let us now convert this into a two-stage operation. So, when we say two stage operations, its first stage will contain 30 tons of propellant and 9 tons of inert mass which will burn first.

So that at the end of the first stage operation you will have 50 tons of mass left that is the first term in our velocity expression, but now you will find that you will not start from 50 tons the next stage. You will get rid of the 9 tons of inert mass of the first stage before you start the second stage. The second stage we started only 41 tons, burn the 30 tons propellant and end up with only 11 tons of final mass of which 2 ton will be the payload and 9 ton will be the remaining shell of the second stage which anyway cannot go anywhere.

And we realize that in this process that velocity increment is almost of the order of one kilometre per second. Fairly significant increase in your; velocity capability by just converting into two stage operations. Let us now go to three stage operation. In three stage operation, first stage has only 20 tons of propellant and 6 tons of inert mass. So, the first term is $\frac{80}{60}$ and now using the same strategy that we have done in the two stages we remove 6 tons from 60 tons so that we start only with 54 tons.

But another 20 tons of propellant and reach 34 tons at the end of second stage and then remove another 6 tons from this 34 and start with 28 tons for the third stage operation which ends up at the end of the mission as 8 tons of which 2 ton is the payload and 6 ton is the shell. You can clearly see that if I were to now do this let us say for 4, stage or 5, stage incrementally the inert mass which is connected to the payload will start reducing.

And in the limit if you see infinite stages the final stage will have only the payload and nothing else so that will be the most efficient which means that if you perform this with infinite stages that is the best possible scenario and you can get a best possible velocity. The question is this really workable?

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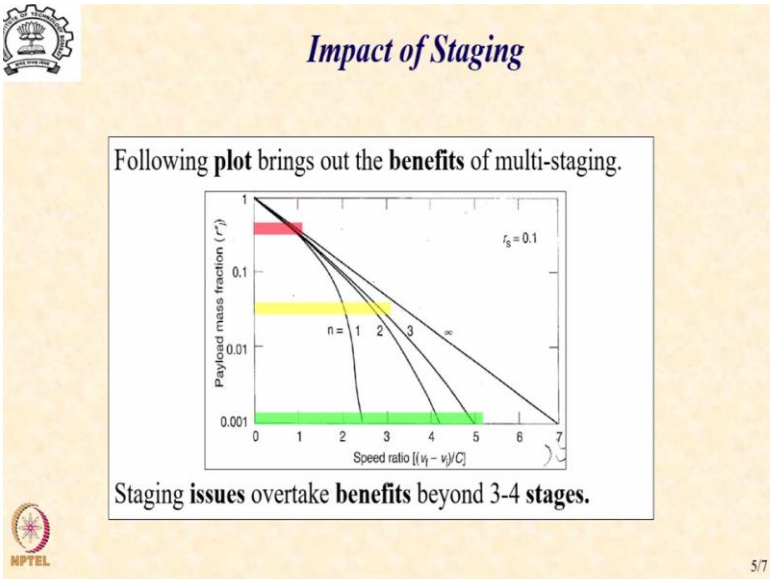

So, let us look at a picture. So, this picture shows a generic scenario that we are likely to get when we start increasing the number of stages. The scenario is created in terms of the two important parameters of the rocket performance that is the payload mass fraction and the speed ratio that is amount of speed which is increased as a ratio of the exhaust velocity. This capital C is the exhaust velocity which is typically of the order of about 3 kilometers per second or most common fuel supplied.

And let us now look at this little bit closely. So, let us first say that we are going to fix the velocity at this point which is about 2.4 times the exhaust velocity which is approximately equal to the velocity required for establishing a circular orbit at around 200 to 250 km altitude that is about 7,500 to 7,600 m/s. So, let us say that we are interested in such a mission.

Now in single stage operation we immediately realize that you are going to get only one kg of payload per 1,000 kg of the lift off mass that is the efficiency of your mass fraction. The moment you make the same mission a two-stage mission I simply move the cursor vertically and come to this curve for $n = 2$ and then I move it to the left horizontally and I find that with the same lift off mass, same propellant I_{sp} everything same.

I can achieve a payload of practically 7% fraction which means for every 1,000 kg of lift off mass I can get 70 kg payload 70 times increase just by going from one stage to two stage. Of course, I also see that if I go from two, stage to three, stage the benefit is not very significant even though we are using a logarithmic scale on the vertical side. Let us now argue the other way.

Let us say that we are going to fix our payload requirement as 7%. So, let us come to this part. Now, if I want to have a payload fraction of 7% so that for a 1,000 kg rocket, I would like to have a 70 kg payload I come to $n = 1$ and I find that the velocity I am going to get will be roughly of the order of about 6,000 to 6,200 m/s not sufficient to even establish an orbit which means that if I want to establish an orbit for this payload not possible with the single stage operation.

So, let us now move over to a two-stage operation. Now immediately I see that for two stage operation the velocity will be of the order of 7,600 m/s and we can establish. So, which means that if; I want to launch a 70 kg of payload with a 1,000 kg rocket I must have at least two stage operations. Of course, if I go to a three-stage operation there is only a marginal benefit in the velocity.

But now I see another interesting pattern that if I were to lower my payload requirement to let us say 1 kg per 1,000 kg with a three-stage operation, I can get a velocity which is almost 5 times the exhaust velocity which is almost like saying 12 to 15 km/s it is way beyond escape velocity for interplanetary mission. So, now you can see if that from this picture by bringing in the multistage configuration either you can take a small payload for interplanetary missions or a large payload for near earth missions.

And that is what you will find most of the launch vehicles that same launch vehicle can also serve a space station mission or a mission to moon or mars. It is just a question of appropriately deciding on what payload fraction we are going to use. Of course, we also see from this picture that the infinite stages are not really a workable option for two reasons. One you have law of diminishing return.

So that beyond three stages the actual benefits in terms of percentage are significantly smaller in relation to the complexities that will increase because every time you add a stage you need to create a mechanism that will handle the separation of the inert mass of that stage and will also hand over the control to the next higher stage. So, obviously it is not a very useful concept beyond a certain point.

And that is why you will also find if you look at the data sheet of many vehicles that we have currently with us that beyond 4 or maybe in some very rare cases 5 stages you do not have any rocket configuration. Most of the rocket configurations lie within two, three and four stages. And now we have a basis for using this number of stages.

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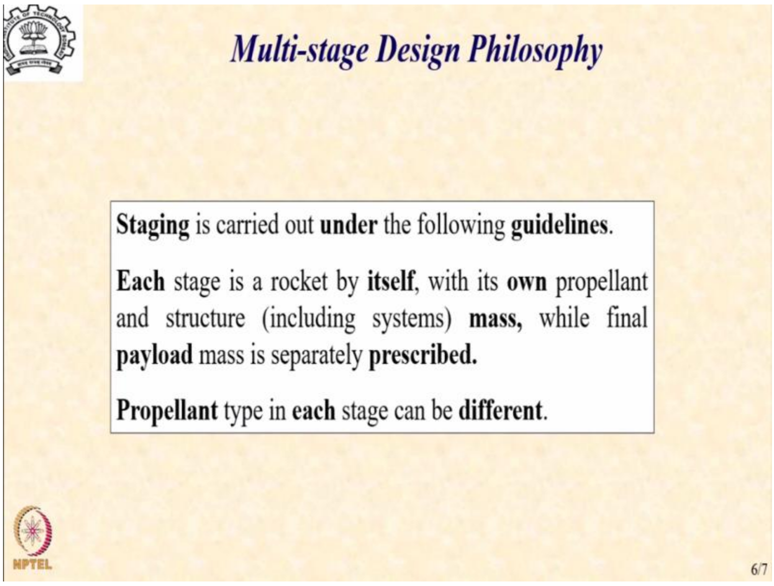

So, let us now understand the broad framework and philosophy within which the staging operation is going to be carried out. So, let us recall and each stage is a rocket by itself with its own propellant and structure including systems and mass which is altogether termed inert mass. While the final payload mass is separately prescribed as m^* as we have seen in the examples.

So, this is the terminology that is going to get used from now onwards that m^* will always be used as the final useful mass that is going to be released in the orbit. And now we have in addition to that other masses for each stage, the inert mass for each stage and a propellant mass of each stage or what we would call the propellant loading of each stage. Of course, in the example that we have seen now we have not really changed the I_{sp} of the propellant.

And you will immediately note that if we do that the performance that we can get is significantly different. For example, if you use a higher I_{sp} fuel in the higher stages the amount of velocity increment that you can get even for two stages is very high and that also is one of the reasons why in most launch vehicles which are used for launching space craft for interplanetary missions, the last stage is typically the cryogenic which has the highest I_{sp}.

Now, you see the reason why the cryogenic stage is the last stage because that is the most efficient stage it is required to accelerate the smallest possible mass. So, the largest amount of delta V we can generate by using even a smaller amount of propellant in the final stage.

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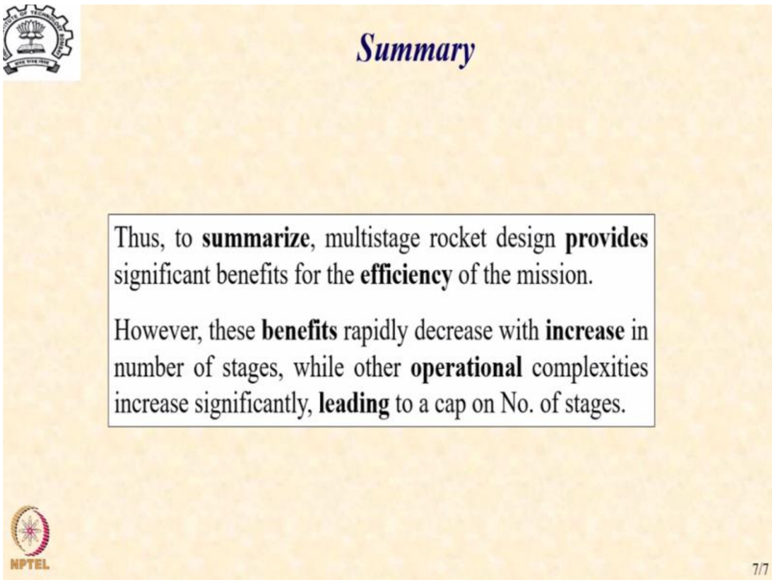

So, to summarize the multistage rocket design provides significant benefits in terms of energy or velocity and also very high efficiency of conversion of the propellant energy to the mechanical energy. However, these benefits rapidly decrease with increase in number of stages. While the operational complexities increase and results in a cap on the number of stages that are commonly employed for most practical launch vehicle to between three and four stages.

So, we have seen the benefit in a broad sense about what multi-staging can do to rocket performance at the terminal point. Of course, we have idealized equations, but as you can see as a kernel or as an idea this definitely has lot of potential to give you a much better performance. And what we will do is in the next lecture we will look at some basic formulation steps that using the framework and the guideline we will be able to setup the equations that will give us the solution for a configuration of the rocket.

That in the multi stage context will give us the desired performance. So, bye see you in the next lecture and thank you.