Introduction to Launch Vehicle Analysis and Design

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Lecture - 24
Parallel Staging Concept

Hello and welcome. Till now as you would have noted we have looked at the series or the restricted staging concept and we have also looked at the solutions. If you recall, I had made a mention of another form of staging called the parallel staging, which also is commonly practiced and we will now talk about it from a conceptual perspective as well as its features and overall benefits. So let us begin.

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So let us begin our discussion on parallel staging strategy.

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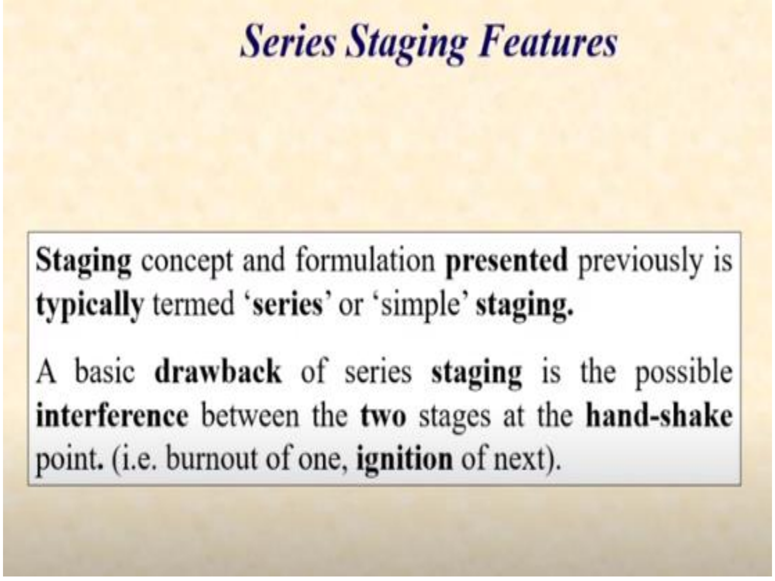

Just to reaffirm, till now what we have done is called a series or sometime also simple staging. Which means, it is a sequential strategy in which each stage operates and then after it is separated, the next stage operates. And this brings in certain constraints that we have seen in the formulation earlier. But there are other issues that such as staging brings in.

One of which is that when you want to drop off the structural mass of the stage which has completed operation, there is now an action which comes in the picture and that action involves removal of a stage and initiation of the next stage. That is also sometime termed a hand-shake point that where the two stages shake hands on each other and then one leaves while the other starts operating.

And this particular point becomes an extremely critical point from operational perspective that how do we ensure that the stage which is completed operation should be removed with as little disturbance as possible and the stage which is supposed to operate starts without any significant delay. Because during this period as you would immediately realize there will be no propulsion on the vehicle.

And that is something which may not be a desirable objective, particularly when you are in the lower atmosphere where there could be disturbances that might affect its overall performance.

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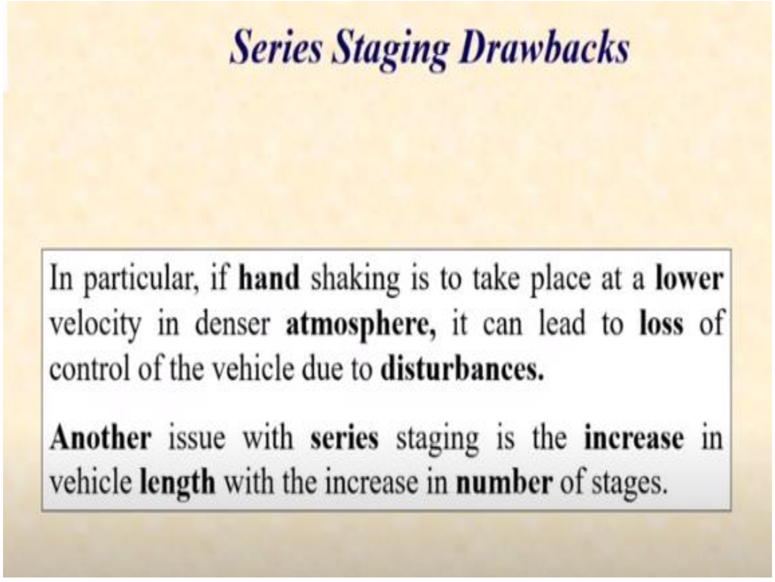

One of the possible repercussions of such a thing happening is likely to happen in a lower velocity in a denser atmosphere. And there have been instances where there has been loss of control of vehicle due to disturbances occurring exactly at that moment when the handshake was taking place. So obviously, you cannot risk it.

Another issue which we have not explicitly discussed, but which is evident from the overall strategy of series staging that as you add number of stages in a serial manner, you also add to the overall length of the vehicle. So, if you go from one stage to two stage or two stage to three stage, the length would keep on increasing depending on the length of the stage which is added.

While the length of the upper stages are generally smaller, it still has an impact in terms of the overall length, which brings in additional issues that we need to understand.

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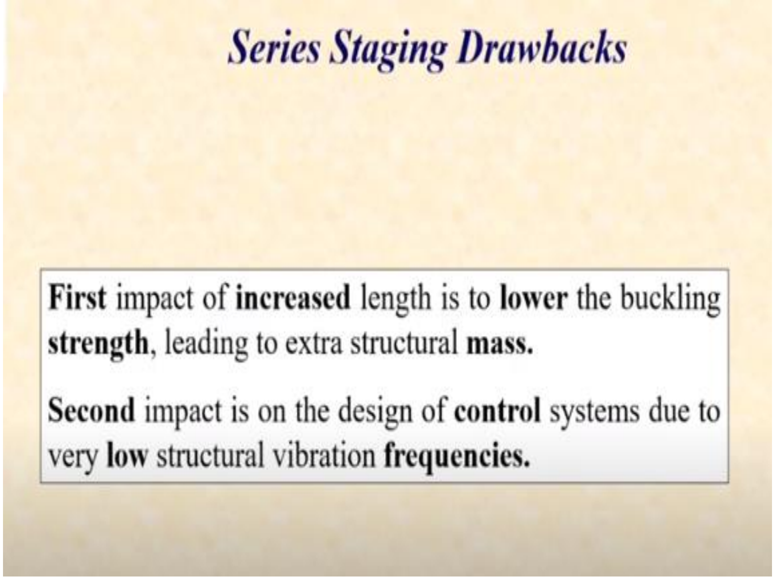

The first impact of this increased length is to reduce the overall buckling strength from a structural perspective. And in order to compensate for the loss of buckling strength, you need to augment the structural mass or the stiffness leading to higher structural mass or an inefficient structure from the propulsion perspective. So, which ultimately will result in a less efficient mission.

The second impact of increased length is that, it results in very low structural vibration frequencies, which sometime can interfere with your closed loop control for the trajectory and there could be issues of stability of the trajectory if structural vibrations are excited due to disturbances.

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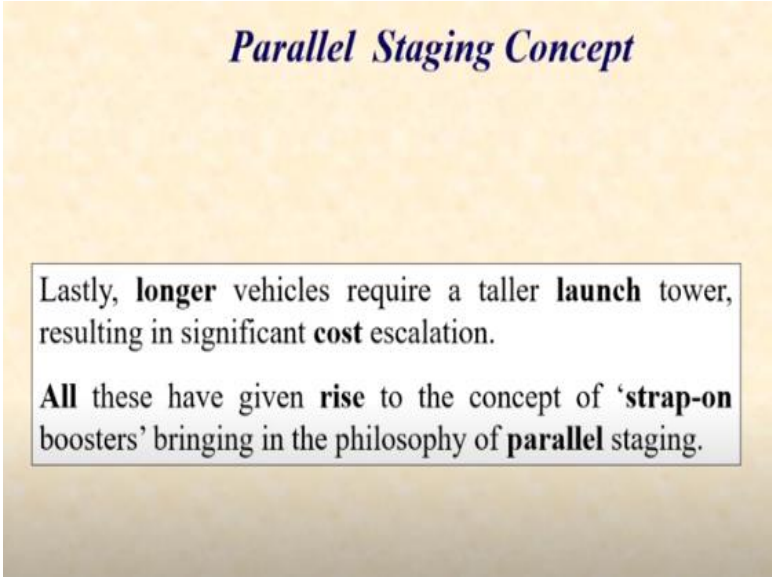

In fact, there is another aspect which is not directly related to the vehicle, but it is related to the launch pad infrastructure. Because, if you have a longer rocket and on the launch pad it needs to be supported at number of points. So obviously, the height of the launch tower becomes higher and higher. And as the launch tower height becomes higher and higher, its design has to change.

And to ensure the requisite strength, its size increases, adding to the overall cost escalation of the mission itself. And this has brought in the idea of using parallel staging which tries to mitigate some of the disadvantages. Of course, as we will note, it also brings in its own issues, but they are of slightly different nature and can be managed better.

So parallel staging is generally a very desirable configurational aspect that most launch vehicles use.

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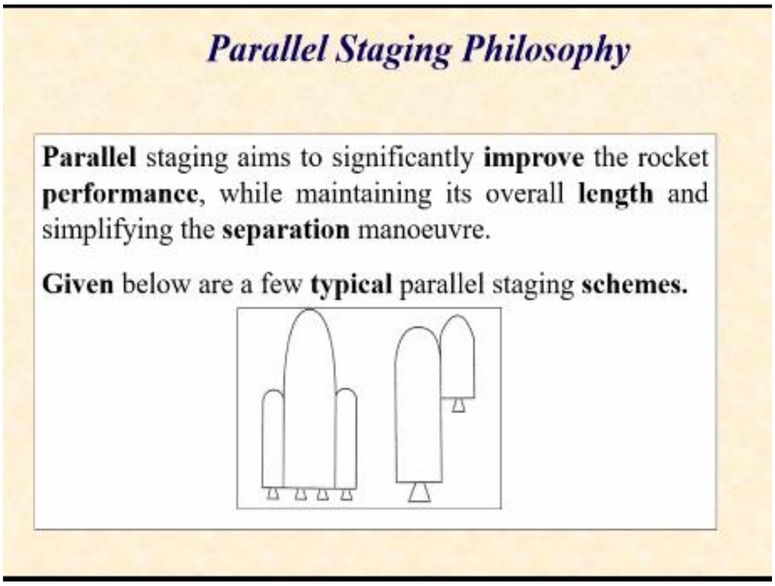

Let us now look at the benefits that we expect to derive from parallel staging. The first thing that is found is that parallel staging significantly improves the performance while ensuring that the overall length remains within the limit. And it also simplifies the separation maneuver. Here we will talk about this a little more when we look at the configuration as to how this particular aspect is addressed.

But let us first look at a few schematics of how such staging's are done. So, I want to show you two possibilities of the parallel staging which is commonly employed in most launch vehicles. So, on the left side the staging concept makes use of a symmetric placing of additional rocket stages on the side so that the vehicle remains symmetric about its axis.

Whereas on the right-hand side, we have another possibility in which the configuration becomes unsymmetric. And this is sometime also called piggyback staging as a smaller stage is riding piggyback on a larger stage. Let me now come back to the first point about the separation maneuver. You can clearly see that if and when I want to get rid of the parallel stage there is a possibility that I may restart the next stage without having to wait for the completion of the previous stage.

Because in the serial staging if you start the upper stage before the lower stage has been separated, then the hot gases will have an exhaust issue. So, you really cannot do that. But in parallel staging it is possible for you to continue to run the parallel stage while the next stage can be ignited, so that you can avoid the zone of no propulsion, which is the basic benefit.

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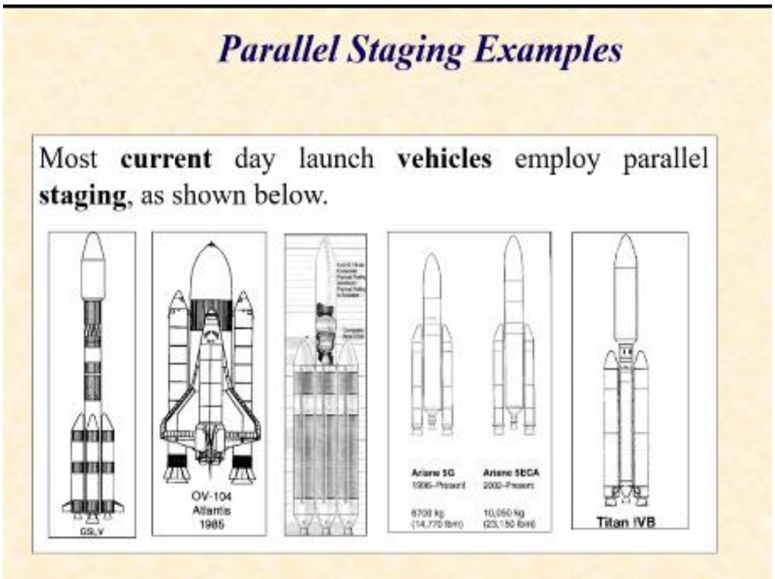

And there are many examples that the current day launch vehicles provide for parallel staging as shown in the schematics below. So, on the left more side, we have our GSLV which has the four strap-on boosters or sometime called the zeroth stage which are symmetrically placed around the axis. Then you have a space shuttle, which has one big core stage. And then you have the side strap-on boosters.

And then you have the orbiter which effectively is in the form of a piggyback stage. So, the orbiter is essentially in the form of a piggyback if you see it from the side view. There is another configuration of parallel staging where the boosters are of almost the same size as the main or the first stage itself. In other two, as we have seen the boosters are of smaller size.

Then you have Ariane, the Titan and a whole lot of rockets which employ the parallel staging concept. As you can see there are many possibilities that we can have for parallel staging.

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PSLV Strap-on Configuration

PSLV has m_0 of **295T** & m_* of **3.5T**, for a mission in **space** station orbit at 407 km **altitude.**

0-Stage: $I_{sp0} = 262s$,	$\varepsilon_0 = 0.182$,	$\pi_0 = 0.776$
1-Stage: $I_{sp1} = 264s$,	$\varepsilon_1 = 0.178$,	$\pi_1 = 0.267$
2-Stage: $I_{sp2} = 293s$,	$\varepsilon_2 = 0.116$,	$\pi_2 = 0.250$
3-Stage: $I_{sp3} = 291s$,	$\varepsilon_3 = 0.106$,	$\pi_3 = 0.444$
4-Stage: $I_{sp4} = 307s$,	$\varepsilon_4 = 0.251$,	$\pi_4 = 0.515$

I just want to show you some data regarding the PSLV now with respect to the parallel stage configuration, or what we call the strap-on configuration. So, if you look at the data sheet of PSLV, the basic PSLV has a liftoff mass of about 295 tons and can launch a payload of about 3.5 tons for admission in the space station orbit, which is at around 407 km altitude.

The overall configuration of the PSLV which can perform this operation is as given below. So, there are structural issues and there are payload ratios. So, I would like you to note that the structural ratio of the zero stage and the first stage is nearly the same. There is no great difference and that is what you will find in most launch vehicles that the booster stage and the first stage typically are of similar configuration.

Sometimes the first stage inventory can be used also as a booster stage so that you do not have to design a booster stage separately. Of course, the higher stages the structural efficiency becomes better except the last stage which is your final cryogenic stage which is supporting the spacecraft. So here because of additional structural mass because of the payload adapter, your structural efficiency becomes a bit poor.

And if you look at the propulsion or the payload fraction, then you will find that the payload fraction for the zeroth stage actually is quite large indicating that the actual mass of the zeroth stage is not quite large. It is reasonably small quantity. But let us look at the actual numbers.

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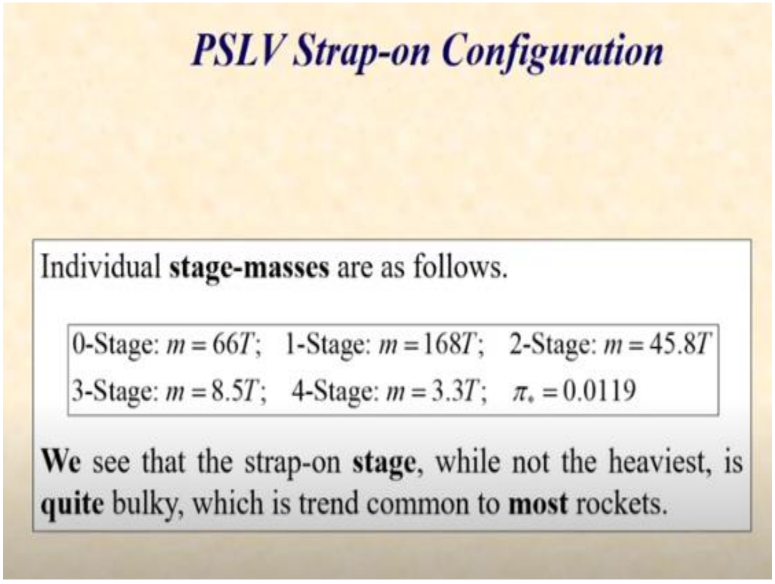

And if you look at the actual mass of the zeroth stage of PSLV it is 66 tons as against the first stage mass of 168 tons which is about one-third, a little more than one-third of the first stage mass and it is more than the second stage mass which is only 45.8 tons.

So, if you now look at this data, you can immediately see that while the strap-on stage may not necessarily be the heaviest, of course in some cases it could be, the strap-on stage is reasonably bulky, which is a trend common to most rockets. Typically, the strap-on stage will be made reasonably bulky so that it can generate reasonable amount of thrust and propulsion capability, particularly in the lower atmosphere.

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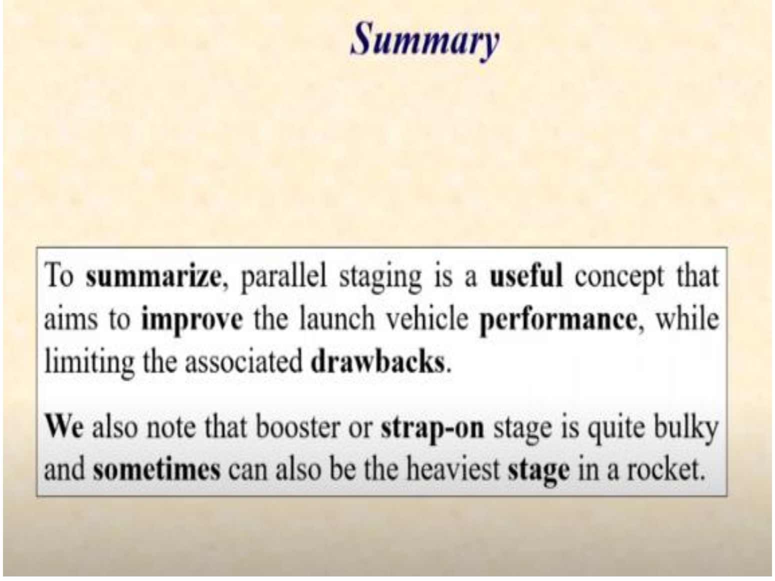

So, to summarize, parallel staging is a useful concept that aims to improve the launch vehicle performance while limiting the associated drawbacks. We also note that booster or strap-on stage is quite bulky and sometimes can also be the heaviest stage in a rocket. Hi, so you see from the preceding discussion that bringing in the ideas of parallel staging brings in not only design benefits, but also operational conveniences that make the vehicle easier to operate and also ensure its integrity during flight.

Of course, the issues regarding the separations are now different compared to a series staging and they have to be handled in a different manner. There is another aspect which is not explicitly noted, but is important is the fact that the area around the base where the booster stage is connected significantly increases the frontal area of the rocket compared to series staging.

And as you will realize that this increase in frontal area is directly responsible for a higher amount of drag coefficient because of scale friction and other separated flow phenomena which occur in these regions. So, you will find that there is a small penalty that we need to pay for having the rocket with booster stages in the form of additional drag that the vehicle will suffer.

In the next lecture, we will look at the additional details and we will look at some of the design related issues that we need to handle when we have parallel staging. So, bye. See you in the next lecture and thank you.