Jet Aircraft Propulsion

Prof. Bhaskar Roy
Prof. A. M. Pradeep
Department of Aerospace Engineering
Indian Institute of Technology, Bombay

Lecture No. #34
Engine Component Matching and Sizing

We are talking about matching of engine components for aircraft engines. In the last class, we talked about matching of a typical turbojet engine components, and we saw there a number of issues that need to be addressed in the process of matching various components. And we know that aircraft engines are not only turbojets, but you have the turbo fans, and you have various other variants like turbo shafts and turbo props.

So, today we will first take a look at what kind of matching you would do to achieve a matched core engine. Now, all these engines that we talked about for aircraft application do have what we call core engine which is compose of the high pressure compressor, the combustion chamber, and the turbine. So the matching of the internal components - the inner most components is the first thing that needs to be done, and of course that is the thing that needs to be done in all variants of engines

So, we will first take a look at what you need to do to achieve a matched core engine, and then we will take a look at what you need to do, if you wish to have matching of let us say the free turbine or the power turbine which is often required for turbo fan engines or turbo prop engines, so the matching often the proceeds in a manner in such a way that the LP components, and the H P components are matched first separately. So first we will take a look at how the H P components are matched to begin with because they compose the core of the engine of any of kind of jet aircraft engines that we are talking about. So, let us take a look at how the core engine is matched.

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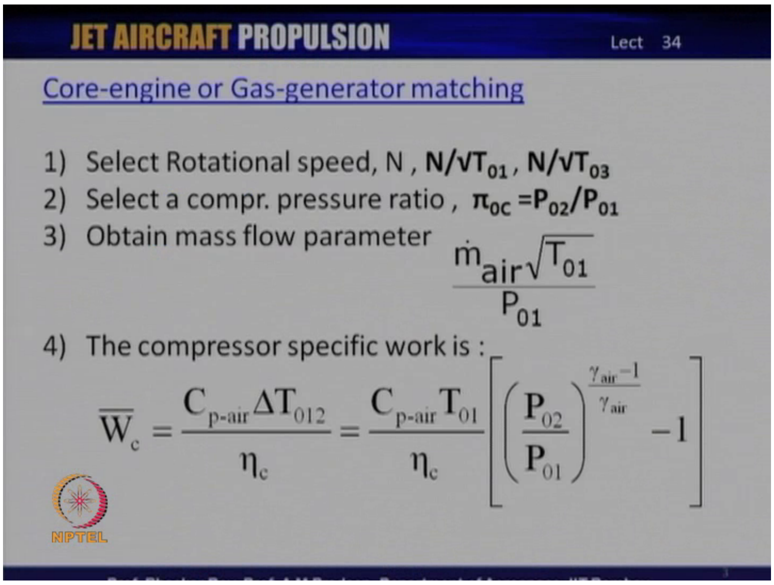

The core engine is quite often also referred to as the gas generator simply, because it also produces the hot gas which of course, runs the engine, and hence quite often many people refer to its simply as a gas generator. Now the core engine as we know is composed of the HP compressor, and the HP turbine and some are between them there is a combustion chamber.

The matching of the rotating component so the compressor and turbine of course, is the of more important issue here. Because the number of things that need to be taken care of so let's take a look at these steps which leads just towards the reasonable matching procedure. If you take the basic mechanical matching requirement it is necessary that the speed of the compressor, and turbine are to begin with matched.

Now, if you do that you see in terms of the non-dimensional parameters that we have talked about earlier it gives us two parameters here; one with reference to the compressor which is normally non-dimensionalized or normalize with reference to the compressor reference temperature which is often T 0 1, and the turbine is often normalize with reference to the turbine operating temperature, which is often the turbine in the temperature that is T 0 3, and hence we get 2 normalized parameters out of 1 single rotational speed.

So, when we go to the respective compressor, and turbine maps they will probably take us to two slightly different speed lines; one with reference to the compressor map, and other with reference to the turbine map; and these are the two speed lines we would need to match with each other in the matching procedure.

The next thing we need to look at is borne out of this speed line, which was defined for the compressor we need to figure out the compressor pressure ratio, which is pi 0 C, and that is the total pressure ratio that we are talking about. And this total pressure ratio then needs to be achieved at normalized mass flow which we have to find in the last class m dot air a root over T 0 1 by P 0 1.

Now this is something, which you are familiar with that the mass flow parameter needs to be normalized what we see now is that in the compressor itself the normalized speed the pressure ratio, and the normalized mass flow parameter needs to be first found on the compressor map. And that is the first important thing that one needs to do, because that particular point on the compressor map would have to be eventually matched with a equivalent operating point on the turbine map.

Now borne out of these parameters; we can see what should be the compressor specific work. The compressor specific work can be written down in terms of as we have done before W C bar, and this is specific work that is work done per unit mass flow, and that is given typically in terms of C P air delta T 0 1 2 divided by the efficiency compressor efficiency, which is often relatable now to the pressure ratio as we know, and this pressure ratio is something what we got earlier as a compressor operating point.

So, we need to relate the work done now to the pressure ratio that is operating, and this is specific work if you want full work you have to multiply this with the mass flow that is operating through the compressor.

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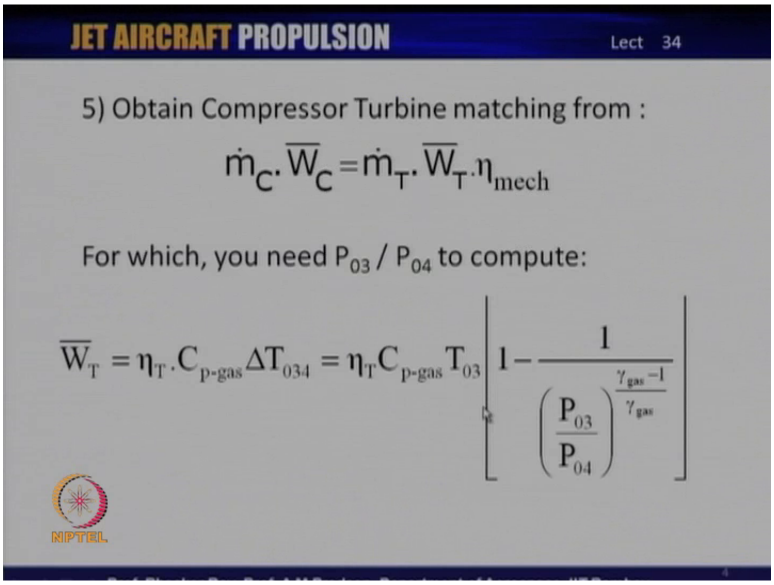

Now, if you find the compressor work, then the next thing to do would be to find the matching turbine work, now that is the work that the turbine needs to supply to the compressor to achieve that compression ratio. If you do not supply that work compressor is not going to give you that pressure ratio. So, it is incumbent on the turbine to supply that much of work now this is the full work and not specific work; So, we multiply the compressor specific work with the compressor mass flow and on the right hand side we have the turbine mass flow and the turbine specific work, and multiply it with all that the mechanical efficiency of the shaft which transmits the power from the turbine to the shaft.

Now, to get the turbine specific work you need to find out from the turbine map what the value of pressure ratio should be across the turbine which is P 0 3 by P 0 4. Now, this is relatable to the turbine work. Now, as we have done before the turbine work can be related to the turbine efficiency the C P and the delta T across the turbine, and the delta T can be now written down in terms of the pressure ratio across the turbine, and this if you do that you get the specific work of the turbine, and this specific work multiplied by the flow through the turbine gives you the work that needs to produce by the turbine to be supplied to the compressor to achieve that pressure ratio.

Now, if you do that then at that particular operating point of compressor, and at this operating point of turbine that is P 0 3 by P 0 4, and the speed line in root over T 0 3 that gives you the operating point of the turbine. So, now we have operating point on the compressor map and we have operating point on the turbine map, which are said to be matched to each other. So, we have only 1 point on each map that are matched to each other.

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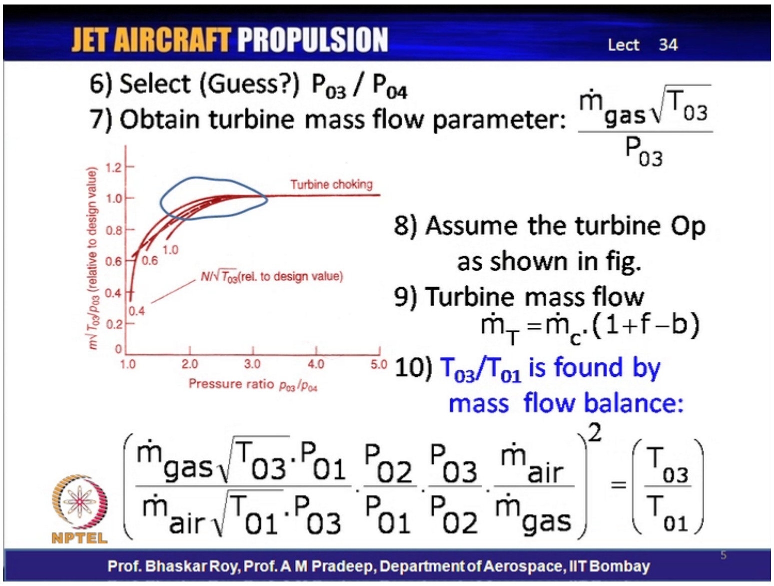

So, what is necessary to complete this matching procedure is to begin with we have to supply that work. We know that, the work needs to be supplied, so to supply that work we got to figure out what the pressure ratio should be we do not know that apriori, and we can make a reasonable first calculation and from which you can make one can say an assignment or a guess of what the value of P 0 3 by P 0 4 are to be. If you do that, then you get on to that a come a turbine map, which gives you the turbine normalized mass flow m dot gas root over T 0 3 by P 0 3. Now, that is the point which you are looking for on the turbine map.

Now, remember the turbine map is normally plotted with pressure ratio on the x axis, and the normalized mass flow on the y axis; And if you do that the various speed lines that you have of N by root over T 0 3, and if it is related to the design value you get them in terms of percentage or in fraction of 1, and at speed line of 1 you are on hundred percent or that is on the design speed line.

Now, as we can see here the various speed lines and this we have seen before in your turbine chapter various speed lines converge to one single line, and that is because all the speed lines have finally led to choking turbine flow. This choking turbine flow then proceeds as a single line for all the speeds, and irrespective of any further change of pressure ratio the turbine remains choking, and once it is choked given the turbine given the geometry, given all the blades the coking mass flow is not going to change any more for any speed line what so ever.

So, it reaches a maximum choking point or maximum mass flow point on this map. Now, this is the point where we got to find a point here, which will match with our compressor operating point. Now, the point essentially here you see is that once the turbine is choked irrespective of your choice the pressure ratio there after the mass flow or the normalized mass flow that we are looking at will remain constant.

So, it does not matter what pressure ratio you choose from here onwards of the turbine operation that is P 0 3 by P 0 4 as you see on this map; whatever pressure ratio you choose, you can continue to increase your pressure ratio across the turbine the mass flow is not going to change. You can change the pressure ratio across the turbine by either allowing the back pressure to fall down by operating the nozzle or by any other means your mass flow is not going to change any more.

So, you need to choose your P 0 3 by P 0 4 operating turbine pressure ratio very carefully here. To ensure first you have the work done that is available, so your P 0 3 by P 0 4 is to be chosen on the basis of work done that is to be available, and as we can see here once we are on this flat plato of the turbine map the mass flow is going to remain constant. So, you have choice of P 0 3 by P 0 4 would be essentially governed by the work done requirement from the compressor, and the mass flow through this operation is likely to remain constant, once it is reached the choking condition

Now, if you get the turbine operating point from that first; let us say a guess or educated guess or a calculated guess you get the turbine operating point, and from this you get the turbine operating mass flow, which you say to be let us say choked, most of the turbine that the designer would like to have an operating point which is indeed actually choked.

So, the turbine mass flow would need to be found from this operating point and that would be found with the help of some corrections which you required for addition of the fuel that is F, and some amount of bleed that may have been imposed on the compressor flow. The bleed is normally as you know taken out for various servicing of the engine or the aircraft.

So, when all those corrections are applied you get the turbine mass flow. Now, that is the turbine mass flow which you need to put back in your work done matching, which we did in the last slide we can go back here, and this is where you got to come back and put your turbine mass flow to get your exact compressor turbine work matching. This has to be exact there is no scope for being inexact over here. Now, if you do that you get a operating turbine mass flow from the pressure ratio we have got, and from the turbine mass flow that we have got we can find T 0 3 by T 0 1 using the mass flow balance.

Now, if you use the simple algebra you can get the mass flow balance of m dot gas by m dot gas is of course, the turbine mass flow, and m dot air is the compressor mass flow, and if you simply use the normalized mass flow parameters that we have been looking at, and if you do all that, and line them up all the pressure ratios that are operative across the compressor the turbine, and the combustion chamber. And this is something we did in the last class also if you do all that you get the turbine pressure ratio across the pressure ratio that is operative in the engine the cycle pressure ratio.

Now, this is the pressure ratio that the cycle is supposed to be designed for and this is what we get now from mass flow balance between the compressor, and the turbine.

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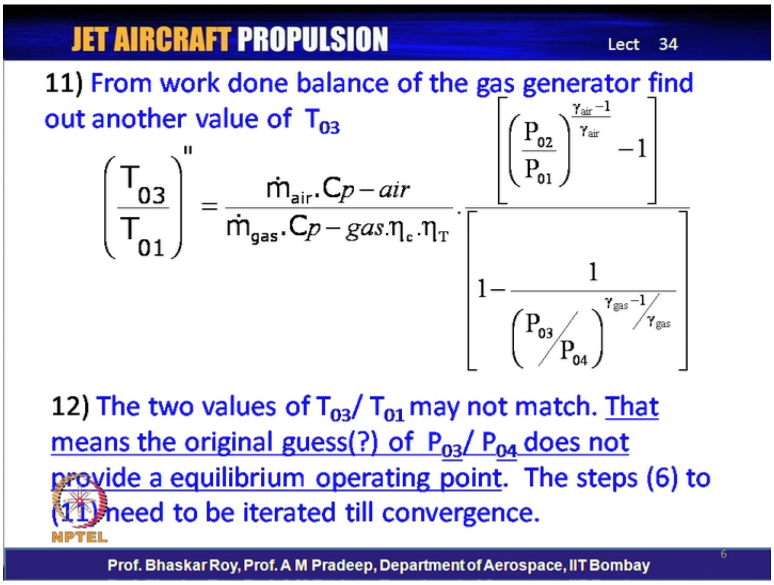

On the other hand, if you do the work balance between the gas generator components of compressor, and turbine if you write down the mass work done using the mass flow of the air, and the gas that is compressor and turbine, and the operating efficiency is the compressor and turbine and the pressure ratios valid across the compressor and that valid across the turbine. And if you again put them together you get T 0 3 by T 0 1. Now, this could possibly be another value, so I have put here 2 0 3 by T 0 1 prime. Now, this T 0 3 by T 0 1 double prime may not quite match the earlier value which you got from step number 10 that is from the mass flow balance that we have across the gas generator.

So, you see you can get two different sets of T 0 3 by T 0 1; one from the mass flow balance and other from the work balance and to begin with they may not match if they do not match you need to go back to step six, which is of your a work balance, and carry through to step eleven all over again till the two values match that is work balance that is T 0 3 by T 0 1 from from work balance, and that found from mass balance the gas generator components compressor, and turbine are not exactly matched.

So, till that matching occurs you need to do this iteration till you reach the equilibrium operating point of the gas generator components compressor, and turbine. Now, if you look at let us say matching of a power turbine.

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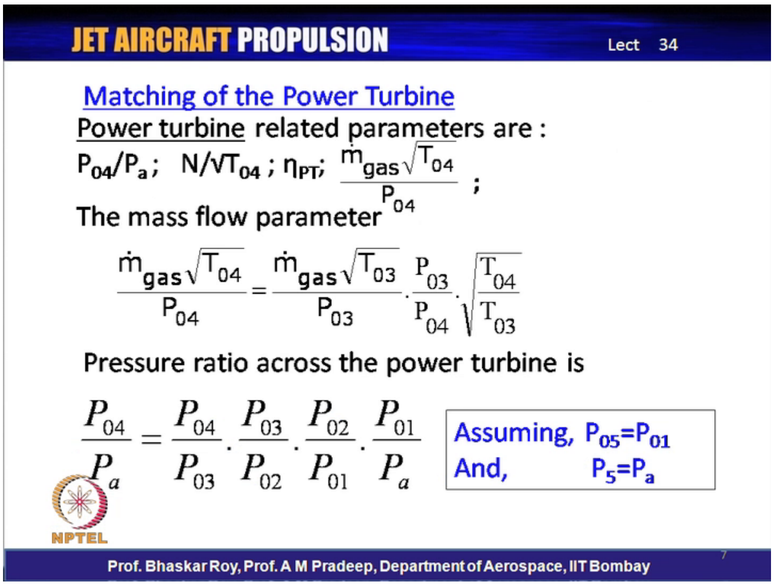

Now, power turbine or free turbine as it is of use we use the word power turbine, because it is often used for powering the a fan or the propeller, which often is used in a two spool engine, which means the power turbine, and whatever it is powering that is fan or propeller is on a separate shaft, which is a power shaft and this needs to be matched again separately; other than the core generator ma or the gas generator matching that we have done just now.

So, let's look at the matching of power turbine. Now, again here you have the power turbine related parameters to be begin with you have the pressure ratio which is P 0 4 by P a assuming that at the exit of the power turbine you finally, have to deliver it to atmospheric pressure that is the assumption at this moment let us say, and then of course, we have the power turbines speed line which is again N by T 0 4 this N could be different from the earlier N.

So, strictly speaking we should probably be writing in 2 which definitely going to be different from the gas generator n, and then you have the power turbine efficiency. We have to assign or make a reasonable guess or what efficiency would be or the turbine designer may have given some idea what this efficiency is likely to be, and then the normalized mass flow through the power turbine m dot gas root over T 0 4 by P 0 4 T 0 4 P 0 4 of course, are the a temperature and pressure at the entry to the power turbine.

So, now we are dealing with the power turbine so we should take the temperature and pressure in front of the power turbines corresponding mass flow parameter if you take this is the on the left hand side of the mass flow parameter of the power turbine. On the hand side, if you start with the mass flow parameter of the gas generator or the main turbine you can arrive at by using the P 0 3 by P 0 4 pressure ratio across the turbines, and the T 0 4 by T 0 3 the pressure ratio temperature ratio across the main turbine.

Now, T 0 3 P 0 3 where the temperature and pressure in front of the main turbine. So, if you now use the pressure ratio across the power turbine that is P 0 4 by P a to begin with with the assumption that it is delivering to P 5 which is equal to P a, and correspondingly the P 0 5 is equal to P 0 1 which is the entry temperature to the engine. So if we make those somewhat simplifying assumptions at the moment. We can line up the pressure ratios that we are aware of the pressure ratio across the turbine the pressure ratio across the compressor combustion chamber the pressure ratio across the compressor, and the pressure development in the intake.

And if you line them up it gives us what the pressure ratio ideally should be across the power turbine, when it delivers again back into the atmosphere. So, that in a simplistic manner tells us what the pressure ratio should be across the power turbine and the above here gives us what the mass flow parameter the normalized mass flow parameter should be in the power turbine.

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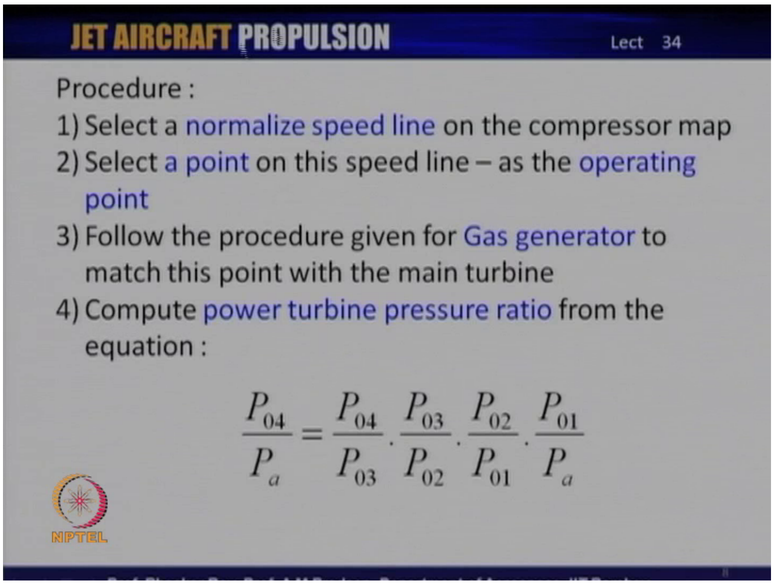

If we look at the procedure that we need to do its somewhat similar to what we have been doing first you got to select a normalized speed line on the compressor map that is the compressor, which the power turbine is driving, and select a point on this speed line as the operating point. So, first you have to find this speed line and then which could be let us say the design speed line, and then a select a point on this speed line as the operating point to begin with again it should be probably that designs a point.

Ah later on of course, we would need to do the off design matching exactly point by point in exactly the same manner then of course, you have the procedure for the gas generator which we have done before just a while back if you follow the same procedure again for the main turbine. We arrive at compressor power turbine pressure ratio, which could be found again firstly as we have just now done from the pressure ratios which are operating across the various components just preceding at the main turbine, the combustion chamber, the compressor, and the intake which were before the power turbine, and if you line them up they all finally, give you the power turbine a pressure ratio again of course, as we have assumed before that it is delivering to atmosphere.

So, if you follow the procedure that we have done, and follow the pressure matching we can arrive at a pressure ratio. Now, we got to find that it mass flow parameter for this free or power turbine.

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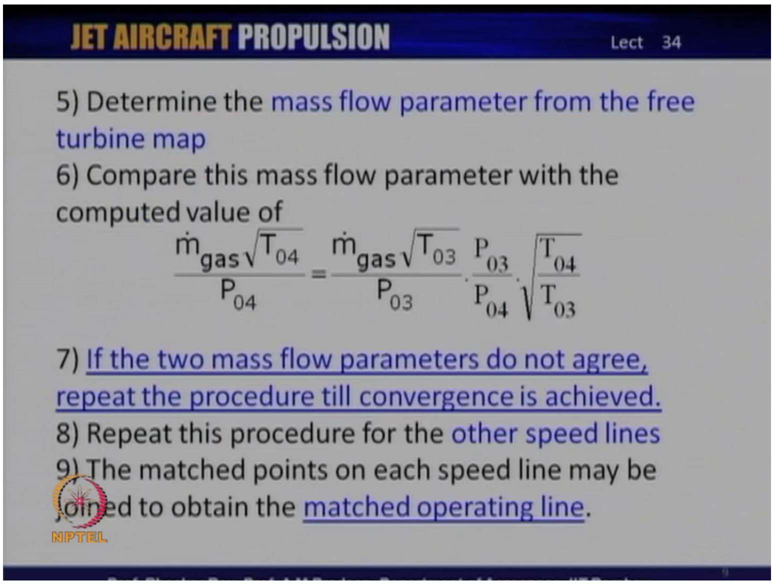

Now, this needs to be found from the turbine map, which must have been generated by the turbine designer. Now, this mass flow parameter with can be computed from again using the mass flow parameter of the turbine the pressure ratio across the turbine, and the temperature ratio across the turbine. Now again we see here, just as we have done in the gas generator case we have two mass flow parameters; one found from the mass flow matching over here, and the other found from the pressure ratio matching which gives us a mass flow parameter.

Now, from the turbine map so we get two values; one from the mass flow parameter from the turbine map on the basis of the pressure ratio that we have calculated using certain simplistic assumptions to begin with and then a mass flow parameter directly from the equation here, and now we can see that it is entirely possible that to begin with the 2 mass flow parameters may not match with each other. In which case, the earlier four steps that we have done before would need to be repeated or iterated till the procedure gives a convergence of the two mass flow parameters. And if we do that, then we get a matching point on the turbine map with reference to a matching point on the compressor or fan map which this a turbine is driving.

Now, we can repeat this procedure these seven steps for all the others speed lines, and many other off design operating points, and at each of these operating points these parameters need to be exactly matched there is no scope for inexactness over here as I mentioned before, and so we got to have the matching points of all the speed lines, and all the operating points there, and if we do that and then we can find a locus of the matched operating points, and we call that the matched operating line.

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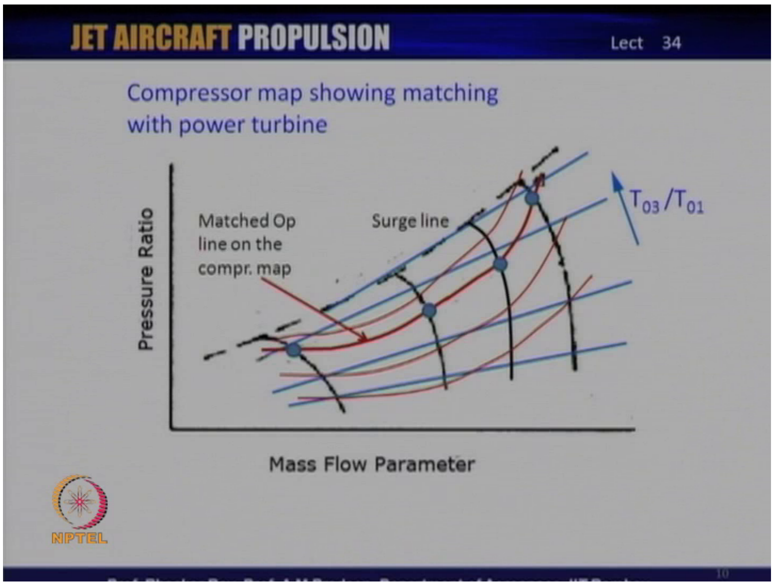

If we look at the map over here on the compressor map let us say the pressure ratio mass flow parameter compressor map these are the speed lines, which we are familiar with you have done that before in great detail in your compressor chapter. Now, if you look at it we can see that they also have the constant temperature line temperature ratio line that is operating across the turbine, and now if you find the matching points from the turbine, and the compressor, and you plot them back on the compressor you can find that these are the matching points on the compressor and turbine map.

And if you do that, and if you join these points you get a matching operating line so each of these red lines is a matched operating line on the compressor map which matches with the corresponding operating points on the turbine line, and hence we can call them matched operating line. So, if you are going from one speed line to another on the compressor map and on the turbine map you could go from this point to this point, and you would still on a matched operating line or from this point to that point you could remain on a matched operating line so and the others are the so called off design matched operating lines.

So, one needs to find a large number of these matched operating lines write across the compressor map and of course, you can draw the similar matched operating lines on the turbine map; the reason we look at the compressor map a little more, and normally more in detail, because the compressor typically has more of problems it has a narrower operating zone, and it has a problems of surge as it is shown here. We need to ensure for example, if you see one of the red lines over here it is moving at high speed towards the surge line.

Now, if you operate along that red line it is entirely possible that at a higher speed you could be moving towards the surge line, and you could have moving towards operating point which could lead you to surge. Now, those are the things that the compressor map throws up and as a result quite often we would need to take a look at the compressor map along with the matched operating points a little more closely before we decide where the engine should operate quite safely.

So, this is what we get out of the matching of the design point, and the various off design points of compressors and turbines.

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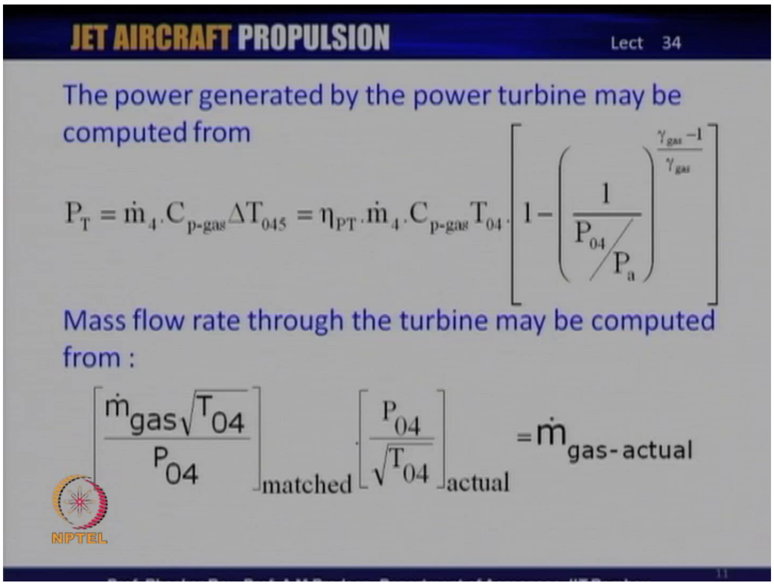

Now, if we do the power generated by these power turbine that may be written down in terms of the parameters that you have done before in compressor, and in turbine chapter the power can be written down in terms of the thermodynamic parameters T 0 4, and then relate that to the pressure ratio across the turbine, and this gives us the power turbine power that is generated, which is to be supplied to the compressor, and this is the power that the compressor would have to do with for creating the compression that the compressor is supposed to create.

Now, mass flow through the turbine now may be computed with the help of the normalized mass flow parameter, which is the matched mass flow parameter that we have got after all these matching, and the P 0 4 by root over T 0 4 that we have got from the actual matching, and if we do that then we get the actual mass flow that is operating through this power turbine. Now, you see this is the mass flow that you need to put back here to get your actual power that is being supplied to the compressor, because the compressor finally, will operate with this actual power that is being supplied by the power turbine in or the second turbine that invariably all the two spool engines have.

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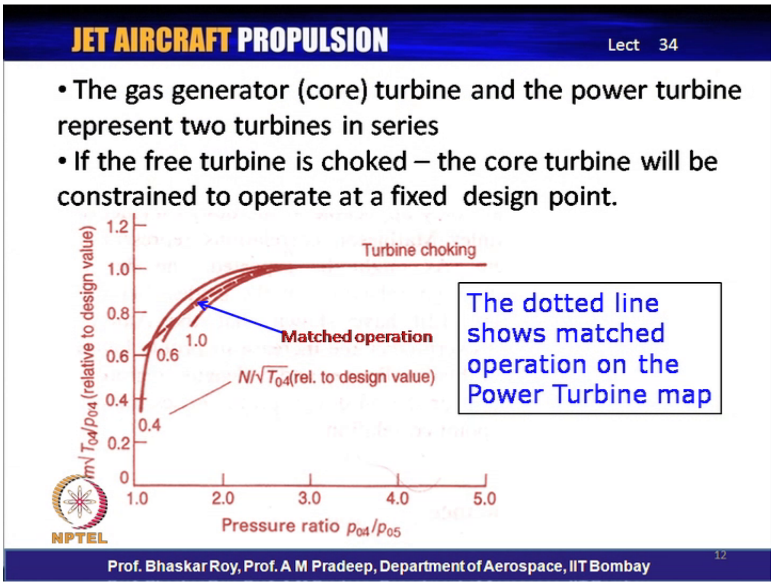

If we look at the turbine map again the gas generator had supplied certain power the power turbine had done its own supply situation, and they are two different turbines we got to understand that these two turbines are operating in series that means the gas flows from one turbine into the other turbine; and it is incumbent that they also have some kind of matching between them. Now, we have seen in case of gas generator that invariably the gas generator most of the turbine operates under choked flow condition that is under maximum flow condition. We can see here, that the if the free turbine or the second turbine set is also choked the co turbine or the gas generator turbine will be constrain to operate it at a fix design point which is likely to be probably choked operating point.

Now, it is entirely possible that it is often the designer would like to ensure that the core of the gas generator turbine always operates under fixed design points, which is normally the choked or maximum mass flow operating point for the turbine. However, the power turbine or the second turbine can get unchoked under certain operating conditions, and we see here one of the possible matched operation, where the turbine may indeed be actually unchoked.

So, this is for your free turbine because the parameters here shown here are with reference to T 0 4, and T 0 4, and the red dotted line if you can see here; shows the matched operating line on the power turbine. This is what I was talking about in a gas generator or a co turbine you would find all the operating points in the chock flow conditions. So, all the match conditions would come on the flat slope over here in case of a power turbine you would in doubt getting a dotted line like this which is the matched operating line on the turbine map of the power turbine, which should match with the similar operating line on the compressor map that we were looking at which is being driven by this power turbine.

So, we need to find an operating line on the compressor map. We (( )) or the fan map and we need to find the operating point on the power turbine map, so that we have two matched lines which are matched with each other by the procedure that we have just talked about.

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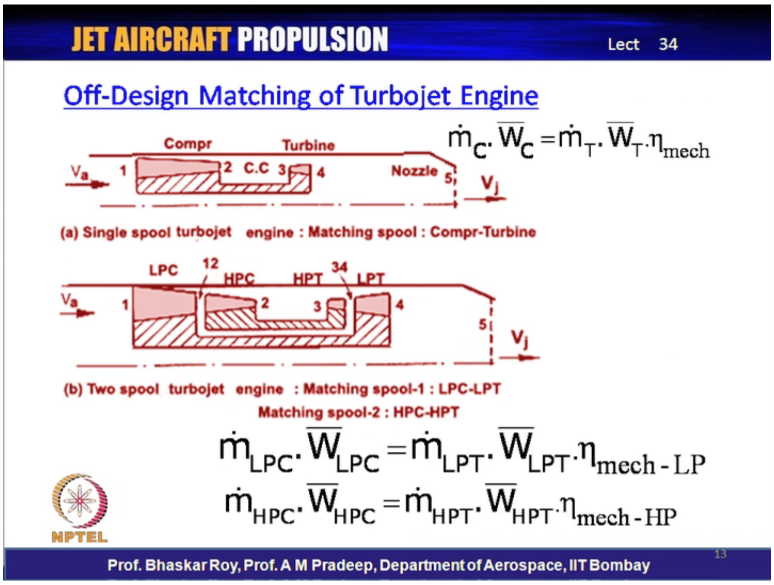

Let us talk a little about off design matching the procedures that we have enumerated just now, would indeed be valid but let us take a look at the major issues that need to be taken care of for off design matching of the engines. If we look at a simple turbo jet engine the matching considerations here are, we need to match the compressor a work with a turbine work that is the first thing we need to now, if we have a single spool engine it is a single spool matching of compressor work with the turbine map.

Now, you have got two spool engine you have two sets of matching here requirement which is the LP C matching with the LP T matching, and the H P C matching with the HPT turbine. Now, the H P and the LP matching procedure would essentially proceed along the same line that we have just enumerated except that the two will have to be done separately, and the matching of the mass flow the matching of the pressure ratio the matching of the work done would have to be done for two sets; one for the LP set and other for the H P set.

And then we have to find the matched value of pressure ratio matched value of mass flow or the normalized mass flow, and then we have to ensure that this work done are exactly matched each for LP as well as for H P, and only after that we can say we have a matched operating point. So, all these needs to be done for one single operating point, and as we know we have a very large number of important off design operating points for each of those operating points this procedure will have to be done very rigorously, and as I mentioned before there is no scope for inexactness here; the matching would have to be exact.

Let us take a look at some other kind of engine. For example, if you look at using power turbine a matching of a turbo fan or for that matter a turbo prop, you would need to again have matching between the fan, and the LP turbine typically fan is run by the LP turbine, and you need matching between the fan and the LP turbine.

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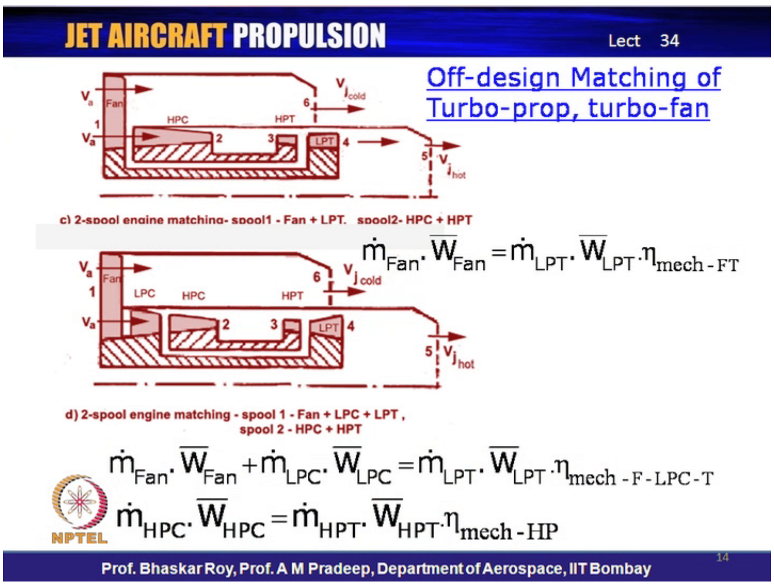

In addition, if you have an engine where LP compressor, and the fan are on the same spool then as it is shown here then you need a matching between the work done by the fan plus the work done by the LP compressor, and all that work needs to be supplied by the LP turbine as is shown here on the schematic, and that needs to be matched exactly and we have the efficiency of the shaft, which is powering the LP compressor fan combination from the LP turbine. And then of course, you have the H P compressor matched with the H P turbine through the H P shaft that is the shaft over here.

Now, this exactly shows that the work done for the H P turbine is to be supplied to the H P compressor for doing the compression work. We need to match the work we need to match again the pressure ratio, and we need to match the normalized mass flow so that on the compressor map of H P, and LP and in case over here you see you need to match the fan, and the LP compressor together with LP turbine.

So, you need to go back to the fan map, you need to go back to the LP compressor map, and then you need to go back to the LP turbine map, and you got to find operating point on the fan map on the compressor map, and on the LP turbine map, and these three points must match with each other, and this is the matching that you need to vigorously and very exactly.

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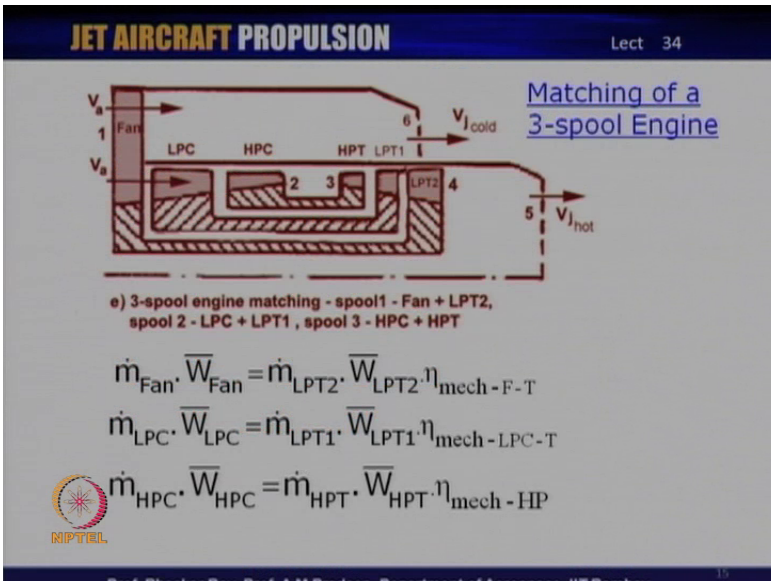

And you got to do this for various off design operating points for which the engine is expected to operate. If we take a look at a typical a three spool matching the entire problem now takes a third fold really speaking that you have a fan mapping, you have LP compressor mapping, and you have a H P compressor mapping with the respective turbines. You have three shafts and three spools, and all three need to be matched in exact manner in terms of again work done in terms of mass flow operating through them the normalized mass flows, and the pressure ratios across these components to be exactly matched, and we got to find operating point on the fan map on the compressor map on the H P compressor map exactly matching with the corresponding turbine maps of LPT2 LP T 1 and H P T.

Only after this is been done vigorously, we have matched operation of all the three spools at any given operating point. So that is the vigor with which we need to do the matching until we do that we do not really have a matched engine.

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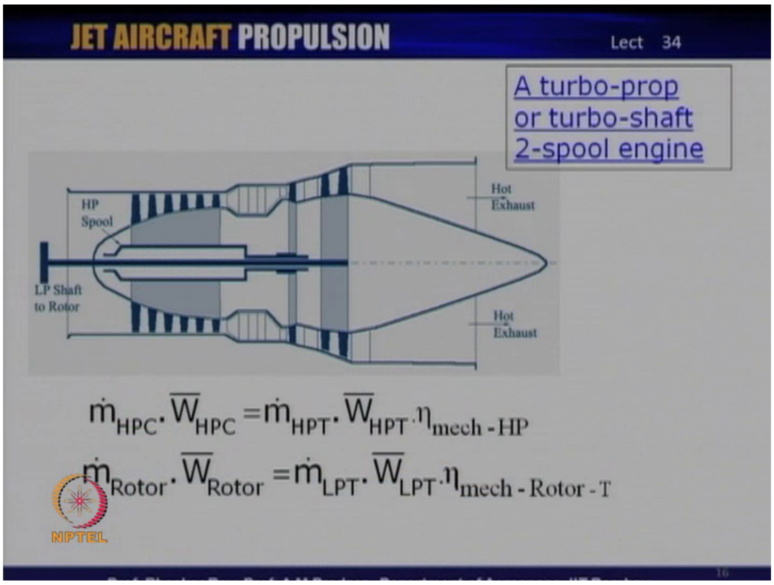

Let us take a quick look at a typical engine that is let us say powering may turbo prop or a turbo shaft the basic engine is of course, the gas turbine engine that we were looking at, and we may look at a typical two spool engine, where the main spool is essentially the gas generator; that is the compressor turbine combustion chamber which we talked about a little while earlier, and we have a free or a power turbine which is powering something straight out of this engine, and it is powering may be propeller of a turbo prop engine or a rotor of a turbo shaft engine. And what is shown here is the gas generator mapping is to be done with the help of the core engine compressor turbine mapping but the compressor mapping needs to be done with the gas generator mapping but the rotor mapping or the propeller mapping needs to be done separately.

We got to find the characteristics or the work done necessary of the rotor or the propeller, and thus power needs to be supplied by the LP turbine for that requirement because that fan that propeller or that rotor is the primary thrust creating mechanism flying the craft.

So, we need to ensure that we have a LP turbine that is supplying the work that is necessary here, the most important thing of course is the work matching we do not have to bother about the mass flow matching here. Because they are two different entities the mass flow working on the propeller is completely different from the mass flow operating on the turbine, and hence we do not have to bother about the mass flow matching but the work matching has to be exact in case of a propellers or the rotors. If the work matching is not exact you have to understand that the propeller or the rotor will not be working at its operating speed or r p m, and if does not operate at the r p m it will not create the thrust that it is supposed to create.

So, the thrust creation of that propeller or for that rotor extremely dependent on the speed at which it is rotating, and if it does not reach its speed it will not reach its speed, if you do not supply the power that is being supplied from the turbine. In case of a propeller quite often if the power supplied is unmatched most of the propellers these days are supplied with or equipped with variable pitch mechanism, and then the variable pitch mechanism will settle it to a different pitch other than the so called design pitch, and as a result of which the propeller might rotate at the speed at which you wanted but it will not be operating at the pitch or the blade setting at which you wanted to be, and as a result again it will not give you the thrust that you wanted out of the propeller.

S, exact matching between the rotor or propeller work, and the work supplied by the turbine from inside the engine is extremely important under design and various off design operating conditions.

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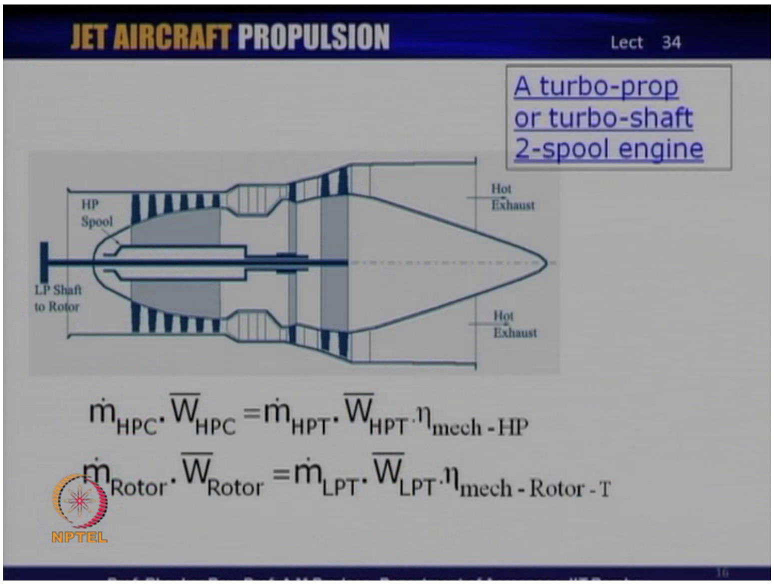

We take a look at a different kind of engine which we have talked about before. Now, this engine has effectively three different matching's that are required; one is the core generator the H P matching the of the compressor on the turbine.

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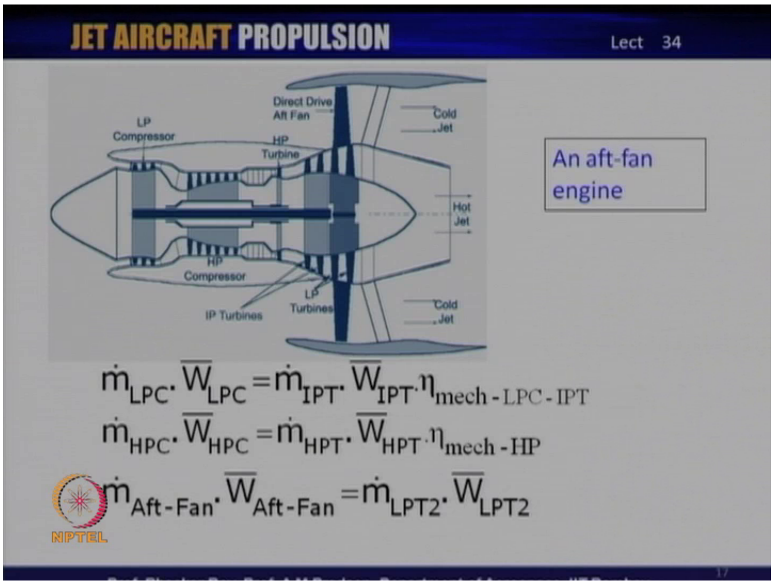

And then we have the LP compressor, and turbine matching which of course, supply power to the LP compressor over here, and then we have the third matching which is the Aft-Fan which is mounted on top of a set of LPT2. It may be two turbines it may be a single turbine and on top of that we have Aft-Fan that is mounted. Now, the Aft-Fan is directly driven by the turbine does not need a shaft, so there is no shaft over here, and Aft-Fan is being directly driven by the turbine which is inside the engine.

Now, since the power is being directly supplied the matching has to be exact between the power generated by these Aft-Fan LPT2, and this Aft-Fan. And this matching again it does not require the mass flow matching, but it is definitely a very exact power matching that you need to immediately achieve and of course, you need to find the operating point on the Aft-Fan operating map or the if you take an Aft-Fan the compressor, which is it is indeed you got to find that compressor or the Aft-Fan map, and all the Aft-Fan map you got to find the point at which the turbine power is exactly matched to the Aft-Fan.

So, again you need to find a point on the Aft-Fan map. You got to find a point of the turbine or LP 2 LP T 2 map, and the 2 should exactly match with each other in terms of the work balance, and this is what mean that when we need matching we need to take care of number of issues in terms of the components that are inside the engine. We got to find work balance we got to find pressure ratio balance or matching, and sometimes we need to take care of the non-dimensionalized or normalized mass flow matching.

In case of it is matching with certain external components like propeller the work done matching has to be exact, and that matching would fully ensure that you get the thrust that you design the engine for, otherwise if the matching is in exact you do not get the thrust that the engine is designed for. So this is what the matching essentially achieves through various kinds of engine that we have been talking about.

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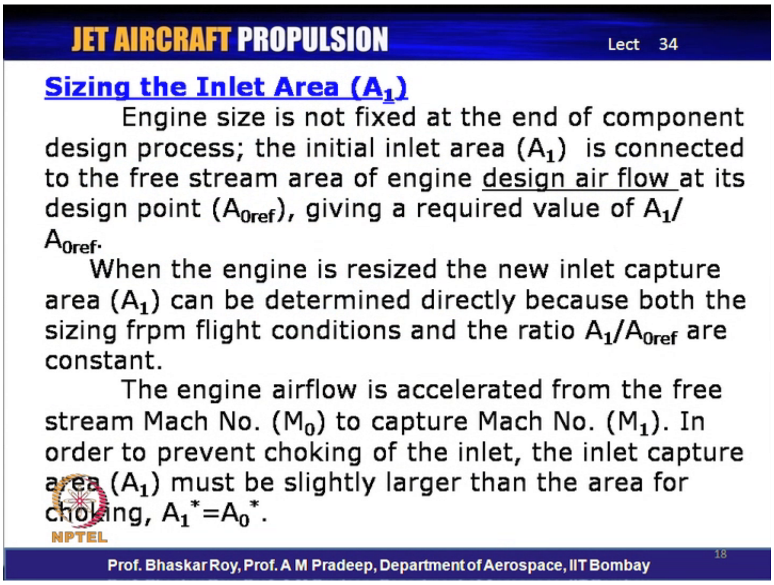

Let us take a look at after the matching you need to ensure that you have an engine which goes with an aircraft for an engine to go with an aircraft, it is necessary that it is a compact engine and it needs to be sized. Now the sizing of the engine quite often it is a fairly comprehensive topic on its own. So, we will take a very very brief look at the two components that essentially dominate the sizing of the engine; the inlet sizing, and the exhaust nozzles sizing.

Now you have done the aerodynamics of inlet or intake or nozzle in great detail in the intake nozzle chapter. We will simply take a look at what the sizing of these two components mean, because once these two components have size, rest of the major components inside would have to be sized within those sizes. So may have the engine size is not fixed at the end of component matching or the component design. We need to find the geometry of the intake, and the nozzles from the free stream aerodynamics that we have been doing quite sometime over our many lectures, and this is done at the so called design point.

That means the design air flow air mass flow that the engine is operating with needs to be considered for sizing the inlet. So, if we take ideal value of the area that is required for the air mass flow to come in this needs to be found with reference to the inlet area that, we need to create for creating the inlet geometry. Now, this capture area this is often called the capture area, which captures the required amount of air mass flow with which the engine can operate at the design point, and create the so called design thrust. This needs to determine, because both the engine r p m for the different for the typical flight condition, and the ratio that is the ideal aerodynamic area, and the capture area are to be held constant during this matching.

Now, engine air flow that is normally accelerated from the free stream Mach number, which could be the flight Mach number to the capture area mach number at the inlet phase of the engine. We need to take into account that there is a little bit of acceleration over there, and in order to prevent the choking of the inlet. If you are not careful it could happen because most of the transport aircraft for example, fly at a flight mach number of the order of 0.85, and if there is an acceleration in front of it before it enters it could actually go into a choking mode.

So, we need to take care of that the inlet capture area quite often is slightly larger than the capture area that would indeed be thought off on the basis of the aerodynamic area that may be calculated easily from the aerodynamics that you have done in your intake chapter.

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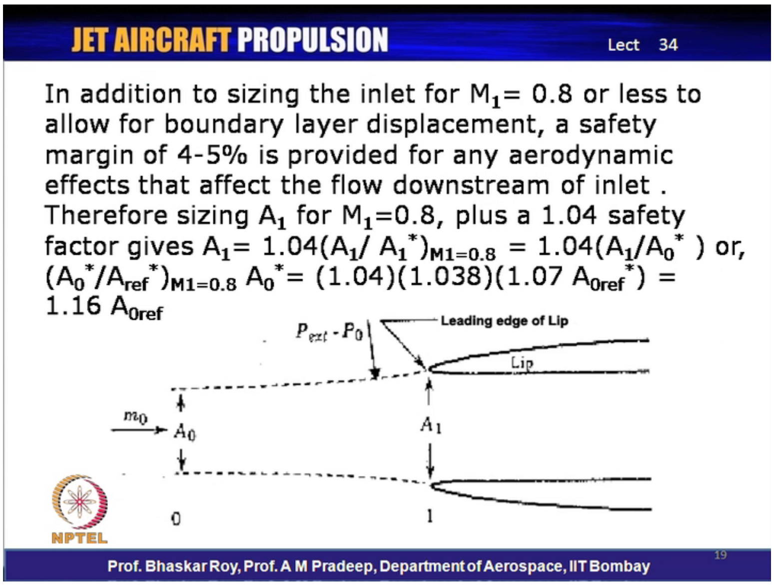

If you look at the simple diagram which you are probably familiar with by now, you have a certain area of the flow that is coming from the free stream this free stream area is supplying flow into this intake, which let us say would have an area A 1, and let us say far off light mach number of 0.8 are thereabout quite often to avoid various kinds of shortfalls, and on one hand, and to avoid choking on the other hand certain simple rule of thumb measures are taken. One is you try to take a 4 to 5 percent margin, safety margin, for the aerodynamic effects that may create a shortfall in the mass flow you remember if you have 4 to 5 percent shortfall in mass flow your thrust production of the engine will fall by 4 to 5 percent directly. So, one needs to take care of that apriori while creating the geometry of the engine.

And then of course, if you apply all the factors over here; one can see here that you could arrive at a final design area, which could be of the order of sixteen percent of the reference area that you get from ideal aerodynamics.

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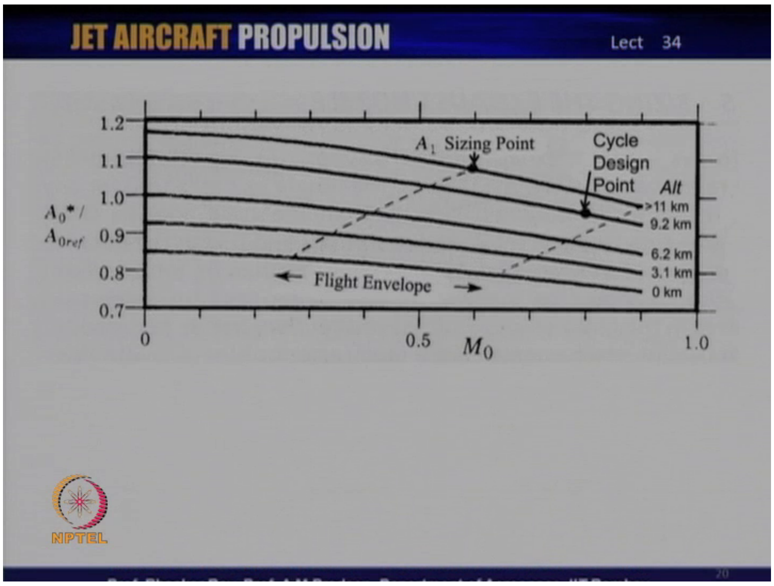

If you look at the map of a typical intake the typical cycle design would give you a point over here, which is fine as far as your operation of the engine at cruise condition which is where your intake is normally designed for on the other hand you might get a sizing point after the sizing that is taking into account the matching of the shortfall of the mass flow. And on the other hand taking into account the fact that under certain condition engine could actually face a choking flow in front of it, avoiding both of them you could arrive at a sizing point, which is slightly different then the intake would indeed look like ;it would be good for flying even at higher altitudes, and at a different mach number.

So, the sizing point could indeed come out to be a slightly different operating point of the aircraft engine than the ideal matching point between the engine, and the aircraft. So, this is the kind of sizing that you would need to do that you need to finally, configure an intake geometry the solid geometry which could indeed be fabricated which caters to all the needs, and it needs to take into account couple of aerodynamic issues that typically could happen in front of the intake, and indeed if it does happen it will affect the entire engine altogether in terms of the performance that you get from the engine.

So, these are some of the simple safety factors that needs to be done to create the solid geometry of the engine body intake is typically the largest part of the aircraft engine, and hence once you have the engine maximum diameter, let us say sized typically that is sets the size of the engine, and as we know typically A 1 or corresponding D 1 quite often is used as a characteristic diameter or characteristic area of the engine for various engine parameter. So this is very simple way by which one can initiate the process of sizing, and as I mentioned before the sizing is indeed very comprehensive method, and it probably requires far more rigorous analysis before one arise at a exact dimension of the components of the engine notably the intake, and the nozzle.

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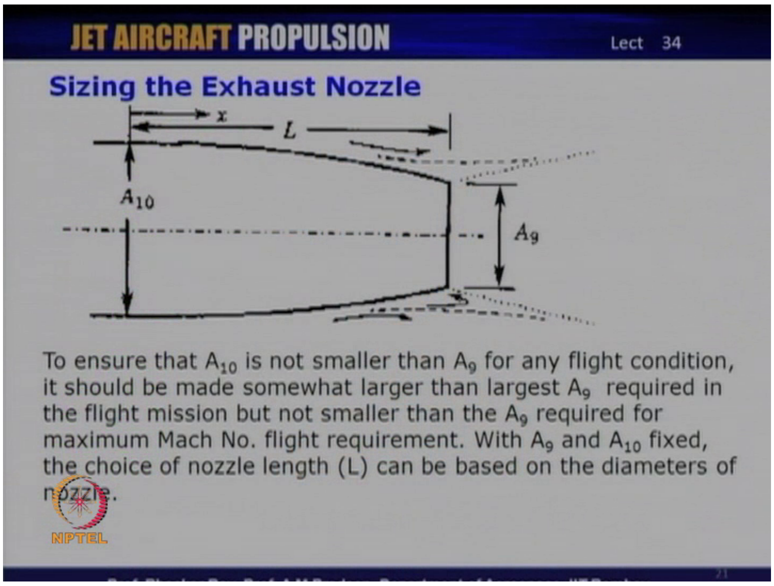

Let us take a very quick look at what happens if you want to size the engine nozzle which is exhaust nozzle. We will take a look at what you need to consider only for the sizing purpose. You see you have nozzle here, which needs to be assigned a certain length. We are talking about creating the geometry now, and we are not talking so much about the gas dynamics or the aerodynamics which we have done before.

You have a certain diameter from which the flow is coming from the inside of the engine that needs to be taken out of the engine, and delivered to the atmosphere through a area let us say some A 9, so it is coming from let us say some A 10 after doing all kinds of work inside the engine. So we are taking some numbers that are very high assuming that all the things that you want inside the engine has been finished, and then it is to be delivered through this nozzle.

Now, what happens is a nozzle has to have two different dimensions it has to have the area let us say two areas; one at the phase of the nozzle entry, and other at the nozzle delivery which is the exhaust area of the all engine. And then you have to assign the length of the nozzle, now length of the nozzle is an important parameter, because that also sets up the length of the entire engine, and the space required for the engine for the mounting on the aircraft.

Now, we see here that we have to ensure that typically A 10 is not going to be smaller than A 9 under any flight condition that will come out of your gas dynamic studies, which you have done before, and on the other hand it should not be larger than the largest A 9 that is required in flight mission; on the other hand it cannot be smaller than A 9 required for maximum mach number flight requirement.

Now, you see when you are talking about intake and nozzle. We are also talking about the aircraft because finally the engine is required for flying the aircraft, and once we are talking about the maximum Mach number it means it needs to cater to the exhaust mach number, and the exhaust flow that suits the maximum mach number of the flight of the aircraft.

So we go to figure out these parameters from the aircraft engine, and aircraft matching. So, there is aircraft engine matching that is coming in here, and once we do that there is another parameter and other issue, which is slightly aerodynamic issues which comes in you can see here that between A 10, and A 9 the length of the nozzle would create external shape of the nozzle this shape is often referred to as boat tail shape, and this shape is important for the drag that is created by the engine.

Now, this drag it is created when the engine is open to the air and not mounted inside the aircraft now this boat tail drag then is contributory to the drag created by the engine itself, and we need to ensure by design that this boat tail drag is minimum. So, in the process of creating the nozzle shape the external shape of the nozzle with reference to the various flight conditions of the aircraft notably the design flight condition of the aircraft needs to be brought in and only then you get the nozzle length, so nozzle length also creates this shape, which is often called the boat tail shape.

So here as you see when we are talking about intake and nozzle and sizing of them. The aircraft comes back into the picture we have to talk about the aircraft so engine is created by the engine designer. But once you are talking about mounting it on an aircraft certain aircraft issues coming into the picture, when you are creating the intake, and the nozzle which are of course, mounted with the engine but they are to be created finally sized after taking into account what is happening to the aircraft, and the flight situations.

So, this is in brief a little bit about the sizing of the engine components and as I mentioned the sizing of all the components is a comprehensive topic of its own and it is beyond the scope of this lecture series. So we have talked about the matching of the components we have talked at very briefly about the sizing of the components all these components, and all these let us say we have a matched engine, let us say we have a sized engine now. And now this is to be matched which means we have to install it on an aircraft.

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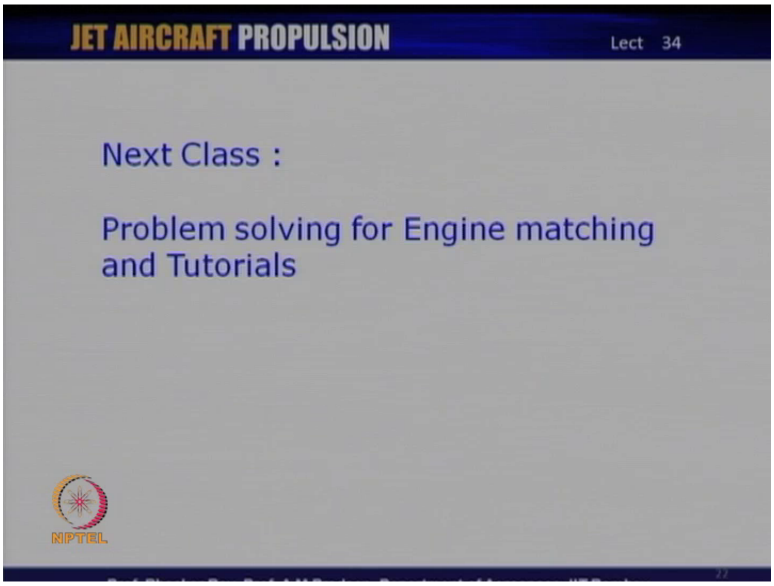

And in the next lecture we shall see what happens when you install it on an aircraft. So we will be talking about the installed performance of an engine in the next lecture, and that is what is there in the next lecture, the installed performance of the engine in the next lecture.