Transcriber's name: Shakeel

Introduction to Aerospace Propulsion

Prof. Bhaskar Roy

Prof. A. M. Pradeep

Department of Aerospace Engineering

Indian Institute of Technology, Bombay

Lecture No. # 31

Tutorial : Propeller

Today we will conclude the lecture series on propellers. We have been looking at lot of propeller, fundamentals, propeller theories. We have looked at propeller theories that provide a basis of propeller estimation, performance estimation, propeller shape estimation, size estimation. One of the theories actually was developed without even considering the propeller shape, blade shape. However, after these coverage's, what we can do is - we can look at the propeller blade shape and we can look at some of the typical propeller shapes, blade shapes, aerofoil shapes, that have been used in the modern propellers, and then, of course, we will conclude the lecture series with tutorial, which means I will bring in a solved problem for you, and then, I will leave you with a few problems for you to solve for yourselves.

So, this series of problems should help you in understanding the theory that we have covered, very simple theories really and it should also help you in creating propellers that, if you would like to create a propeller for yourself, for your small craft that you may be making. So, all this is possible with the simple theories that we have done in the course of last three lectures, and today, we will conclude this series of lectures on propellers.

Today's lecture is mainly about creating the blade shapes to begin with before we take up the propeller problems. The blade shapes that we know are made up of aerofoils as we have seen. Now, some of these blades shapes are very peculiar or I would say original to the propeller blade shapes. The aerofoils that used in propellers are not used in any other applications; they are typically made or designed for propellers only, and hence, we have aerofoil shapes and blade shapes that are typical to the propellers of various kinds.

Now, propellers can be of various kinds. As we have discussed, propellers can be subsonic; they can be transonic. We have not got down to making propellers which can work in supersonic flight conditions. So, even today, we do not have propellers that can fly in aircraft through supersonic speeds; it cannot go through the shocks. The efficiency of the propellers goes down very fast, and hence, they are not competitive to the jet engines, but at subsonic speeds, it is pretty much known that the propellers are more efficient device for thrust making than many of the jet engines.

And as a result of that, at low subsonic speeds, even today propellers are the most preferred form of thrust a making device for aircraft flight, whereas at somewhat higher subsonic speeds, the turbo fans and the turbo jets have their own place especially for long distance flights, but there are many applications of propellers, especially the ones we call turbo props, that is propellers powered by gas turbine engines are used extensively in many medium subsonic to slightly high subsonic transport aircraft both for cargo as well as for passenger. As theoretically propellers are indeed, the most efficient thrust making device.

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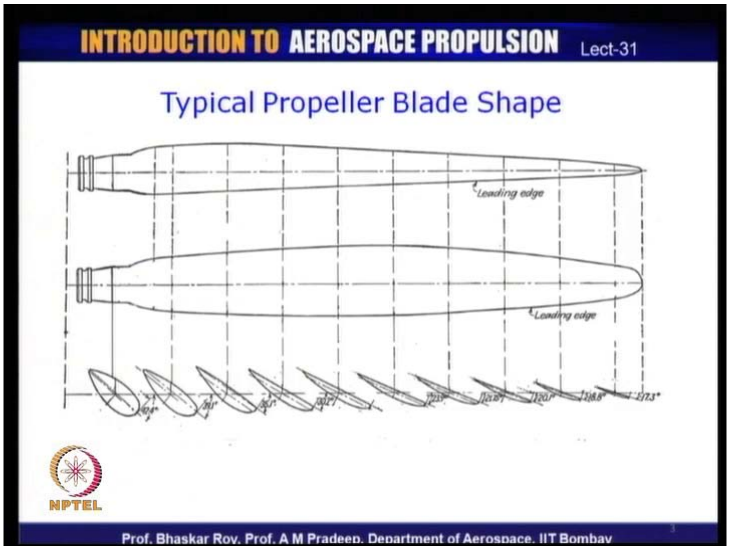

In fact, the propellers are being now redesigned to operate with transonic tip speeds and we shall have a look at such a propeller today. So, let us start taking a look at what a conventional propeller looks like, and then, we will take a look at the transonic aerofoils and a typical transonic modern propeller what it looks like.

A typical propeller, as we have discussed many times, is made up of aerofoils. Now, if you look at this one single blade of a propeller, you can see that along the length of the blade, the aerofoil section or the aerofoil shape changes drastically. Near the root of the propeller blade, the aerofoils are very thick; they could be symmetrical aerofoils. As the requirement here is not so much as aerodynamics, but the requirement here is more of structural integrity and the strength of the propeller. As this entire propeller is held at the root of the propeller, and essentially, structurally speaking, this entire propeller is a cantilever beam in rotation, and as a result of this cantilever arrangement of the propeller holding, the entire propeller load, the aerodynamic load, the lift and the thrust that we have talked about created by the propeller itself has to be born at the root of the propeller and that is where all the stresses strains and the movements are actually finally felt.

So, this portion needs to be made very strong so that they can hold the propeller in rotation. This is something which has to be taken care of right in the beginning of the design, and as a result of which, in this portion of the blade, the aerodynamics is often sacrificed and the structural strength of the propeller blade at the root is given precedence. However, a little after that, especially from here onwards, let us say you need to create propeller blade shapes that help in create a lift and which as we have seen finally help in creating thrust.

Now, the aerofoil section that we choose in these sections are essentially confirming to the local flow. As we have seen in the velocity triangles earlier, the local flow incident on the blade there is typically low subsonic. A combination of forward velocity which we call V infinity and the rotational speed twice pi n r r omega r. Now, at this station near the root, somewhat near the root of the propeller, the local a velocity v r is rather small most likely to be low subsonic, and hence, you use aerofoil section which is indeed a low subsonic aerofoil.

So, the aerofoil section that you choose around here is typically meant for low subsonic usage; they are low cambered but thick aerofoils which confirm to low subsonic application and you need somewhat thicker aerofoil to create a substantial amount of lift, which as we know would then create a significant amount of thrust. However, as you move along, you will find that the aerofoils are becoming thinner and thinner and thinner, and at the tip, it is a very thin aerofoil.

So, they become progressively thin aerofoils, and as we know from the aerofoil understanding, that these are all different aerofoils. These are not the same aerofoils made thinner; these are indeed different aerofoils all together, because at the tip, again if we go back to the velocity fields that we were talking about, near the tip of the propeller, the resultant velocity v r incident on this leading edge is going to be rather high and this is likely to be high subsonic for most of the modern aircraft propellers.

So, you need a high subsonic aerofoil which is normally a thin aerofoil to keep the drag low. Otherwise, the drag would mount very fast. A thick aerofoil which you use near the roots, if you use near the tips would create an almost amount of drag at that high speed, and as a result of which, the propeller efficiency would be extremely low. So, you need to create aerofoil which has a very high lift by drag ratio.

Now, C l by C d as we know is essentially a figure of the merit for aerodynamic efficiency of any aerofoil, and as a result of which, as you go towards the tip from the root to the tip, you have thinner and thinner aerofoil so that you continue to have high aerodynamic efficiency of each and every of this sections, and as a result of which, the overall thrust creation is done with higher propulsive efficiency or propeller efficiency.

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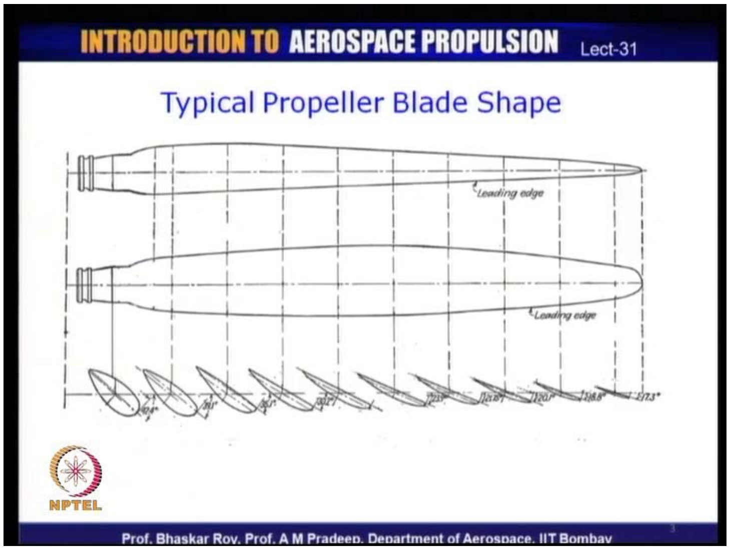

Now, this is the reason, because of which, you have so many different kinds of aerofoils as you go along the length of the propeller from root to the tip of the propeller. The another thing you would notice is near the root of the propeller, the angle at which the aerofoils are set are at high angle, for example, near the absolute root which is actually in inside the root, the angle is nearly 42 degrees, and then, near the next aerofoil which is a proper aerofoil, lift creating aerofoil, the angle is 39.5 degree nearly 40 degrees, whereas as you move towards a tip of the propeller, the angle falls, and near the tip of the propeller, the angle is as low as 17.3 degrees. So, that is the change of the angular setting of each and every propeller and the aerofoils now become what we call? Finer and finer setting.

So, the root of the propeller is set at what can be called a coarse setting and the tip of the propeller is typically set at a fine setting. So, within the blade itself, the propeller aerofoils settings move from coarse setting to fine setting as we move from root to the tip of the blade. Now, this is also confirming to the inlet flow angle 5 which we have seen in the earlier lectures and conforming to the velocity field there; that means a combination of forward velocity and the rotational speed omega r.

So, combination of the two, create this flow angle situation, and then, by design, you attribute or accommodate a small amount of angle of attack which finally creates the blade setting angle beta. So, this is how these aerofoils are selected. This is how these aerofoils are set at these places, and together they are blended into one propeller blade shape, which then creates thrust in a more efficient manner.

Now, as we have seen, choice of these aerofoils, setting of these aerofoils together and blending them into one blade shape create efficient propeller blade, which should be efficient during all times of its operation. Of course, as we know today that all propeller blades today are under variable pitch operating control situation and as a result of which, most of the propellers do have variable pitch controls normally associated with the propeller operation.

If you look at it the propeller blade, this is the leading edge. If you turn the propeller, this is also called the leading edge, which as we will see probably is a comparatively flatter surface. So, if you look at this propeller blade, this is let us say the top surface; so, that is the top surface which as you can see has a curvature, whereas the bottom surface which is the surface, which is we call leading surface. That is the surface that moves forward in rotation so that the surface that needs the air first, and as a result of which, you have a comparatively flat surface, which from aerofoil parlance, that would actually be called often a lower surface or under surface, and we have seen that many of the aerofoils used are actually flat under surface.

So, you can see here that many of the aerofoil that used here actually do have flat under surface aerofoil shape. So, when you put them in the propeller, that surface often becomes the leading surface. So, probably instead of calling leading edge, more appropriate would be to call it leading surface, whereas this is indeed leading edge of the aerofoils. So, this is the leading edge of each of these aerofoils put together, whereas this would more appropriately we should be called probably leading surface and that is the surface that moves into the air first as the propeller rotates.

So, this is how a propeller blade shape is put together created with the help of a large number of aerofoils. Bigger the propeller more is the number of aerofoils that you would need to put together and blending them into one smooth blade shape. As we have seen many of the propellers in the early era - 50 years back, the propellers used to be made up of wood, because that was the easiest material to give complicated shape like this, but over the years, they used aluminium alloys for cast aluminium for giving the shape, and later on in modern propeller era, they are using composite material to give more complicated propeller shapes in most accurate manner. More accurate the blade shaping is in conformity with these aerofoils shapes, more the propeller efficiency is likely to be achieved during actual operation.

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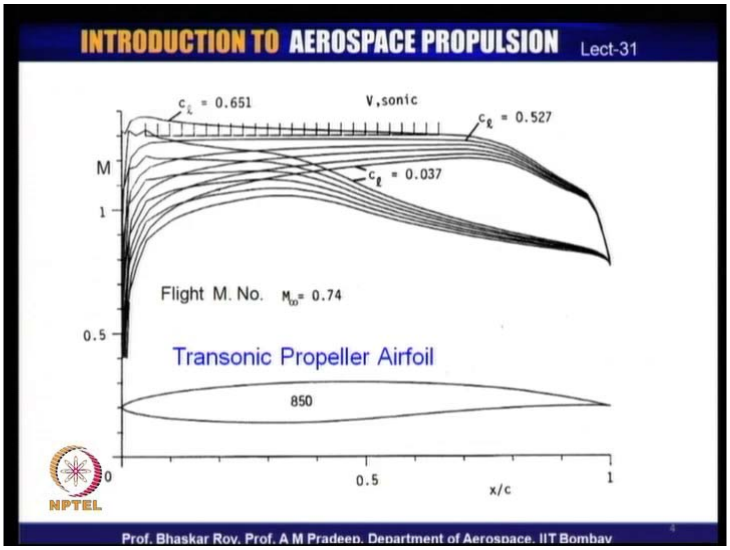

So, this was a conventional propeller shape. I will quickly show you a propeller aerofoil which is meant for transonic applications. Now, this is the kind of transonic propeller aerofoil which is used these days. It can be used in a flight mach number which is close to high subsonic flight mach number, and during such a high subsonic flight mach number, the flow over the aerofoil as we see here can go supersonic.

So, on the surface of the aerofoil, the flow would go actually supersonic even though the entry mach number here is high subsonic, and hence, these are called transonic aerofoils. So, some are over the aerofoil shape, the flow would indeed go supersonic and it is most likely as it shown in the diagram here is most likely to again come out with subsonic profile. Some are on the blade surface, the flow transits from subsonic to supersonic, and then, again transit back to subsonic and leaves the propeller blade subsonically.

So, that is why it is called a transonic propeller and the blade shape that you see here is also created. These are typically computer generated aerofoil shapes and they are created for propellers. These aerofoils are not used for any other purpose in any other kind of aerofoil applications, they are typically created for propellers, and as I mentioned, they are computer generated to confirm to transonic local flow that is expected to be present during propeller operation.

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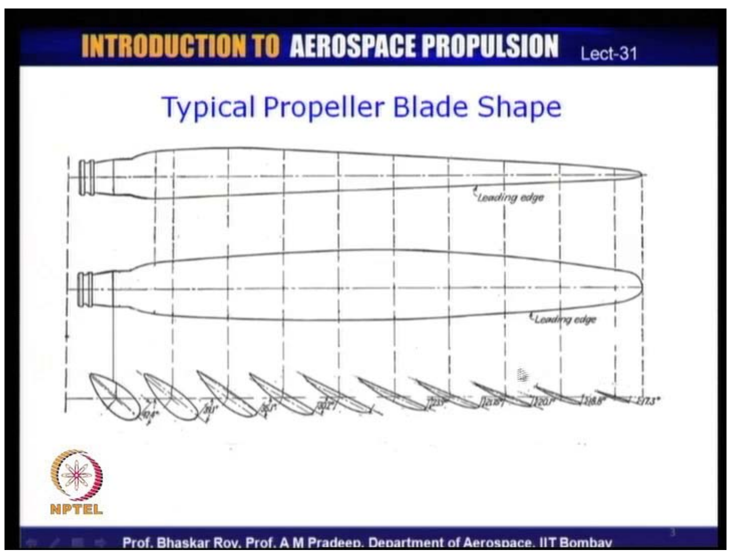

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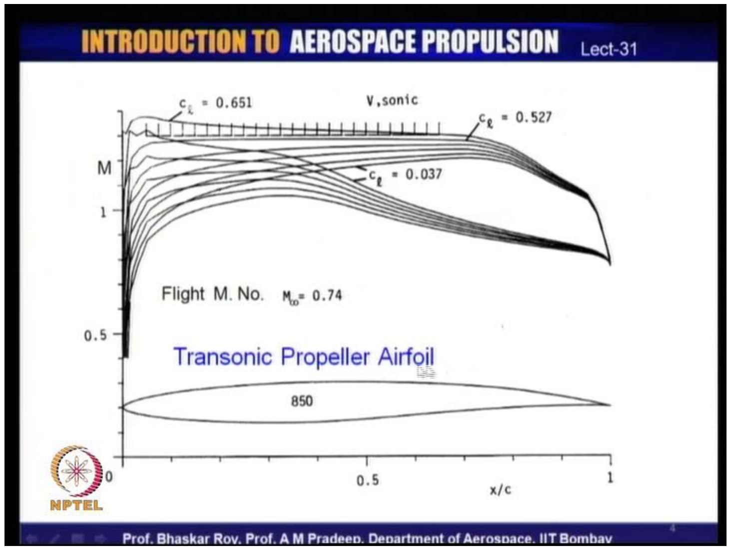

Now, this kind of transonic aerofoil is typically used in the tip area where we were earlier using very thin aerofoils to conform to a high subsonic flow. This is the area where flow is now likely to go transonic in the modern propellers, and instead of these thin aerofoils, thin subsonic aerofoils, the modern designers would like to use such transonic aerofoils where the local flow there, the combination of forward velocity and omega r that is the rotational speed makes the flow actually go supersonic over the aerofoil shape.

So, this is the typical transonic aerofoil shapes, and as we have seen, you need more of these aerofoil shapes to make up an aerofoil propeller or part of the propeller. So, most of these aerofoil shapes are computer generated by the designers and then blended into propeller blade shape. A modern propeller would have transonic blade shapes around here, but it would still have subsonic blade shapes in the lower half of the propeller and they would continue to look something like this; that means they will go even in the modern propellers progressively thicker and thicker as they move towards the root and the root will have to be designed to withstand high stress and strain and the large movement that comes due to the cantilever fixing of the propeller blade. So, that would continue to hold good. However, only the tip section would now be redesigned to accommodate transonic aerofoil shapes, which are nowadays generated typically for propeller applications.

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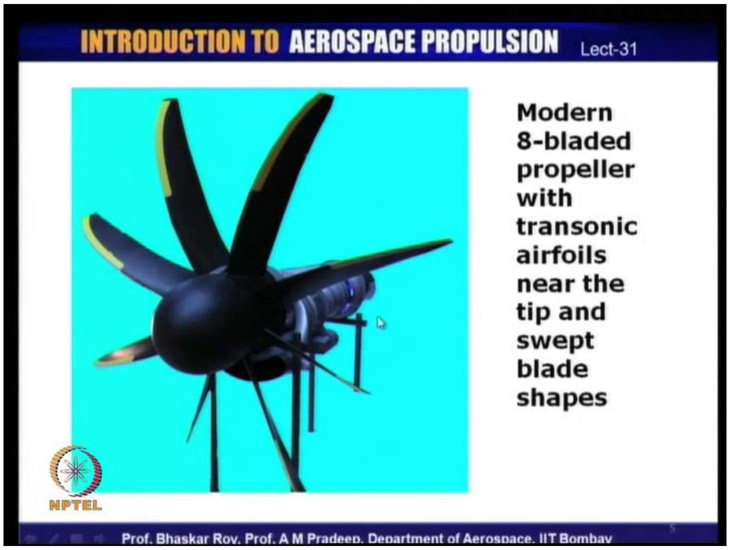

We can look at a typical modern propeller as you can see here, it is made up of eight propellers and each of these propeller is made up of a large number of aerofoil shapes and some of the aerofoil shapes towards the tip of the propeller are very likely to be transonic aerofoils.

Also one can see here this modern blade shape has used a sweep. This sweep is something which is normally associated with aircraft wings. However, many of the bladed machines typically the propellers and compressors and fans are using the sweep for a number of aerodynamic advantages, and especially when the propellers go transonic, the sweeps have certain clear advantages in terms of containing the drag that comes about, and as a result of which, the propeller efficiency is held at a higher value.

So, this is a typical modern propeller with swept leading edge, and as you can see, it has a certain amount of sweep at the trailing edge also and this also uses the transonic aerofoils so that these propellers can be called transonic propellers. So, these are the modern propellers that are used in very modern aircraft, and as you can see here, it uses up to eight blades to create one propeller for thrust making, for aircraft, for modern aircraft which fly at high subsonic flight speeds. Now, we can look at some of the problems which we would like to use the theories that we have done in the earlier lectures and these theories would help you in solving some of the problems.

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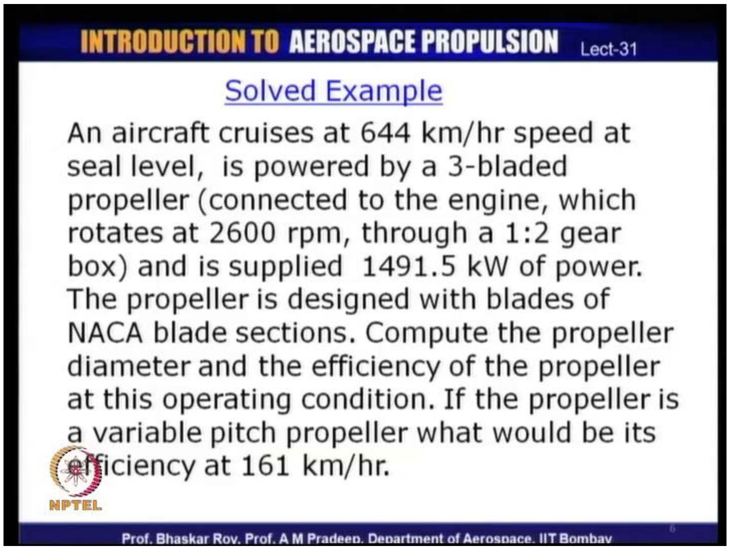

Now, before I give you the problems, I will try to solve a problem for you and this problem is of a variable pitch propeller and this propeller is a little more conventional propeller. What it states here is - it is used in an aircraft which is cruising at 644 kilometers per hour at sea level to begin with and is powered by 3-bladed propeller.

Now, this propeller is connected to an engine which rotates at 2600 rpm, through a 1 is to 2 gear box. So, the rotational speed is actually brought down by 1 is to 2 ratio, which means the propeller speed would actually be half of the engine speed and it is supplied with a power of 1491.5 kilo Watts of power at that particular operating condition, flight operating condition.

It is stated that the propeller is designed with blades of NACA blade aerofoil sections. So, it used the NACA aerofoils which we had looked at before. The question is to compute the propeller diameter and the efficiency of the propeller at this operating condition, if the propeller is a variable pitch propeller, what would be it is efficiency at 161 kilometers per hour? So, our problem is that we have a propeller. That is a variable pitch propeller. It is of course powered by an engine and it is flying or cruising straight and level with an aircraft and it is a 3-bladed propeller.

So, we can use and it is stated that it uses the NACA blade section which allows us to use some of the propeller characteristics of NACA aerofoil propellers, which are 3-bladed propellers. As we have seen before, every kind or every propeller actually should have its own characteristics or characteristics maps as we have seen and we need to use those characteristics to solve these kinds of problems. So, this is a variable pitch problem and I will try to solve this problem for you so that you get a feel of how to solve typically a variable pitch problem, and later on, I will give you some problems which are probably somewhat simpler problems for you to solve for yourself.

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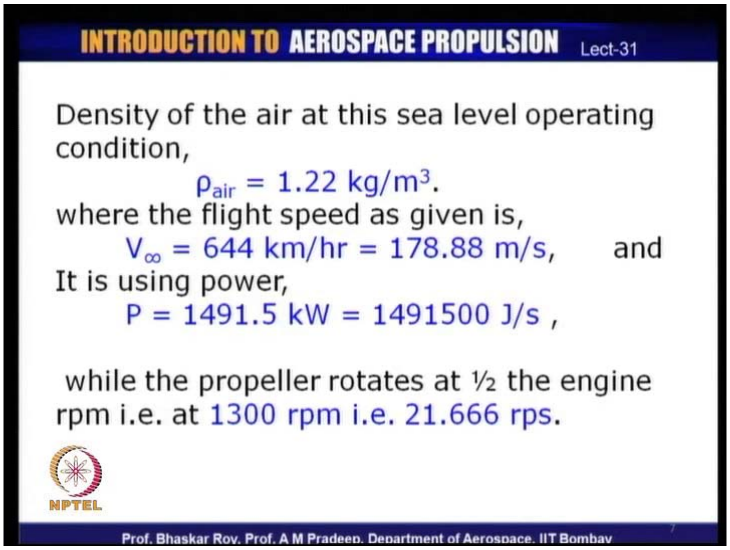

Let us see how the solution of this problem would proceed. The density of the air at this operating condition that is a normal sea level and that is rho air as given as 1.22kg per meter cube; that is the standard air density at sea level and the flight speed is given as 644 kilometers per hour which translates to 178.88 meters per second.

As we know, most of our solutions would proceed with velocities, etcetera, given in terms of meters per second, whereas the normal method of designating flight speed is in normally in terms of kilometers per hour. Now, it is given that it is using power of 1491.5 kilo Watt which translates to 1491500 joules per second; that is as per as the si system, and the propeller it is given that the propeller rotates at half the engine speed through gear box ratio of 2 is to 1. So, it is rotating at 1300 rpm which then translates to 21.666 rps, that is, revolutions per second. So, that is the rotational speed of the propeller.

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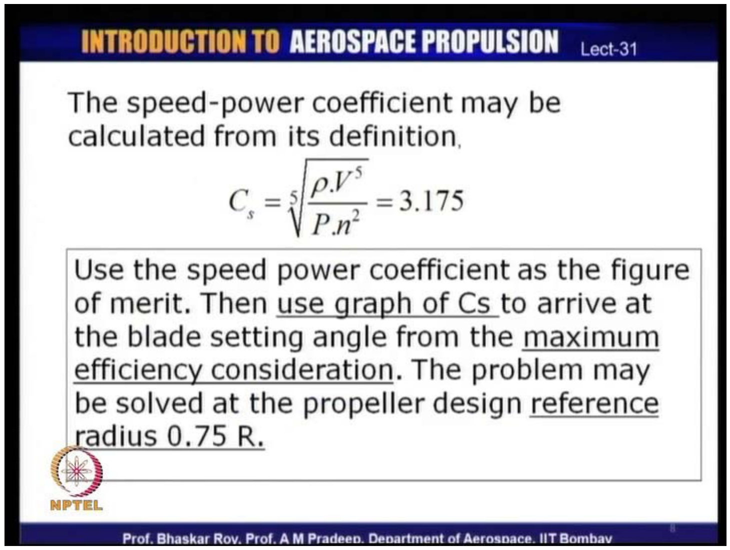

Now, these are the given parameters as given in the problem statement. What we can do is we can look at the first thing, the speed power co-efficient of this propeller given the parameters that are already supplied. Now, this speed power coefficient is something which we had discussed in the last class and we can use it here for the propeller designation. Now, speed power coefficient as from its definition comes out to be 3.175. That is the numerical value of the speed power coefficient, which as we know does not require the propeller size of the diameter.

So, this is one propeller parameter which does not require the propeller dimension for it to be evaluated. So, we have the speed power coefficient as 3.175. So, what we should do is we shall use this speed power coefficient and use the speed power coefficient plot or graph to arrive at the blade setting from the maximum efficiency consideration. We are assuming that we will solve the problem for maximum efficiency of the propeller for this particular blade setting or for this particular operating condition and the blade setting which we will be arriving at. The other thing is the problem is now going to be solved at a propeller design reference radius or 0.75 R, which is often the normal propeller design reference radius, which means the propeller blade shapes are often first created at the 0.75 R.

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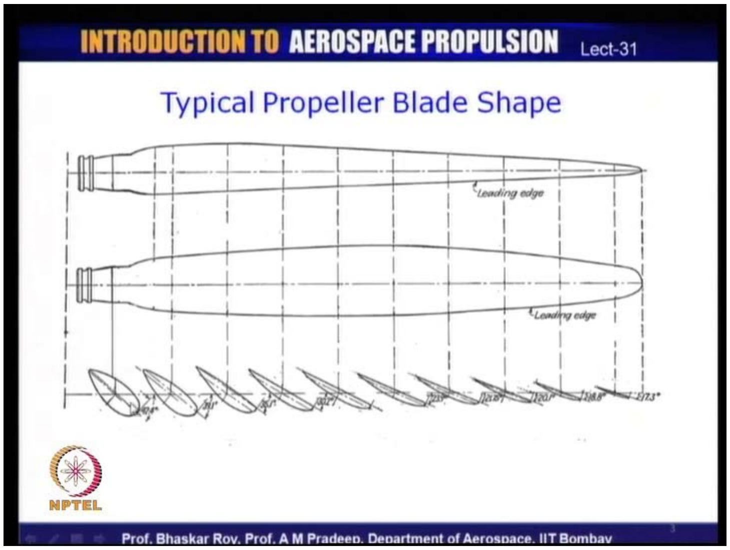

Let us quickly go back to the propeller diagram which we have looked at right in the beginning. You see all these blade shapes need to be created by design. The aerofoils need to be set at various designations, but quite often one starts off with one of the blade shapes which could be somewhere around here, which is to begin with representative of the entire propeller.

So, this particular aerofoil section which is at 0.75 of the radius of the entire propeller. So, if this is, let us say the axis of rotation, the radius of the entire propeller is so much and this is at 0.75 of the radius of the propeller. So, this section would be considered the reference radius or reference section of the propeller and for the design purpose to begin with that represents the entire propeller. So, the performance at that section would be representative of the entire propeller.

So, if you calculate the values of elemental thrust there, that would be an average elemental thrust representative of the entire propeller. So, that is how quite often the propeller design is created, propeller design is preceded that you start off with a representative blade section which is not at 50 percent, which is normally at around 0.75 R and that is where normally the propeller reference radius is often created.

If you have a transonic propeller which we had just look at, the reference radius could be a little higher; it could be somewhere around 80 percent of the propeller blade.

Somewhere over here which is likely to be then a more representative of the propeller blade loading.

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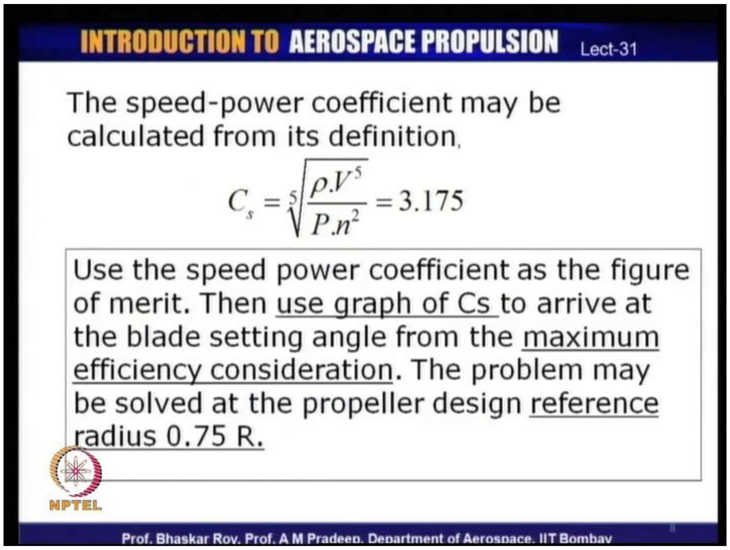

So, propeller reference radius is often chosen during the design and we are going to solve our problem at that reference radius, which is as I mentioned representative essentially of the entire propeller actually. So, we will proceed along those lines.

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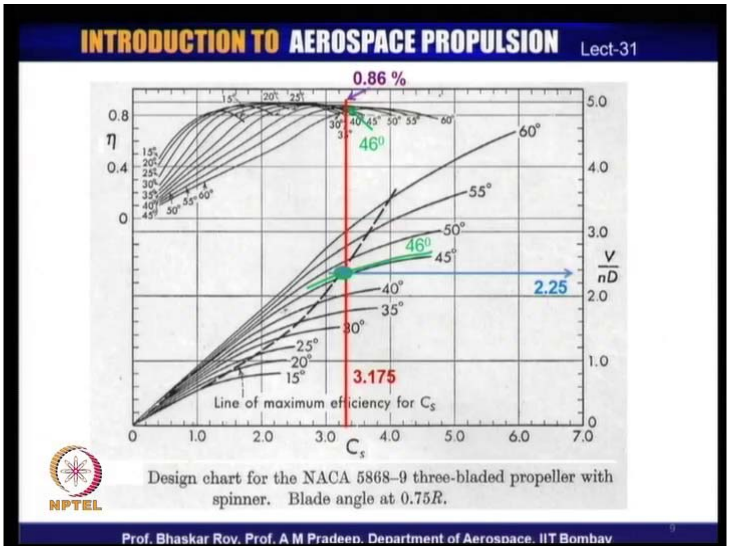

Now, if you look at typical 3-bladed propeller NACA, using NACA aerofoils and the blade is being considered at 0.75 R. If we look at this blade section, blade characteristics, what we see here is the speed power co-efficient C s is shown here in the x axis. The y axis on this side is advance ratio V by n D. On this side, you have the propeller efficiency eta and we have the carpet plots available of these parameters C s versus efficiency and then C s versus V by n D. The other thing that is shown here as variable is the blade setting angle beta. Now, this angles which are shown here are the blade setting angles beta.

Now, as a result of which, as you can see here, higher the blade setting angle, you can go into the higher advance ratio; that means, the higher forward speeds of the aircraft and the propeller which is flying, whereas if you are stuck to a fixed pitch propeller at a lower blade setting angle, you cannot move at a very high speed. So, this is a typical propeller characteristic which allows the propeller to move at comparatively higher forward speeds.

The efficiencies also shown here with various blade setting angles. The lower blade setting angles as we can see here, the range of operation is very small over a very small range of C s and the C s range is extended at higher and higher angles of beta blade setting angle. Of, each of these blade setting angles, you can reach fair good efficiency slightly higher blade setting angles can start giving you efficiencies of the order of 85, 86 percent. At very low blade setting angles, the efficiencies are a little lower of the order of 80 percent. So, if you use typical NACA aerofoil sections and typical 3-bladed propeller, this is the kind of characteristics that is normally available for that blade or that propeller, and if you are now trying to find out how this propeller is going to behave under a particular operating condition, that has been specified in this problem; you would need to use this characteristic map.

Let us use the characteristic map and see where we get our solutions. You see, if you calculate the values of the C s which we have found 3.17, so, this is where you start off with and then you arrive at V by n D, which is the order of 2.25 and you arrive at a solution point which is somewhere over here and you are likely to get a blade setting solution of the order of 46 degrees slightly higher than 45 degree, which has been provided here. So, if you proceed vertically upwards at 46 degree efficiency curve, you could get at this C s an efficiency of the order of 86 percent.

So, in this graph, what we can see is if you use the parameters given and calculate the fundamental parameter C s and the advance ratio V by n D, you can arrive at a suitable blade setting angle for this particular blade section, the reference section. So, the reference section of the blade at 0.75 R should now be at 46 degree blade setting angle. As we know the blade setting angle would indeed vary from root to the tip of the blade.

So, this 46 degree is at the reference blade section at 0.75 R and not for the entire propeller of all the blade sections. So, that needs to be kept in mind and this is a variable pitch propeller. So, this particular blade setting is suitable for that particular operating condition which is specified in the problem. At any other operating condition, you can choose another blade section through variable pitch mechanism and operate at that section to get good efficiency of operation. So, this particular operation now gives us an efficiency of the order of 86 percent.

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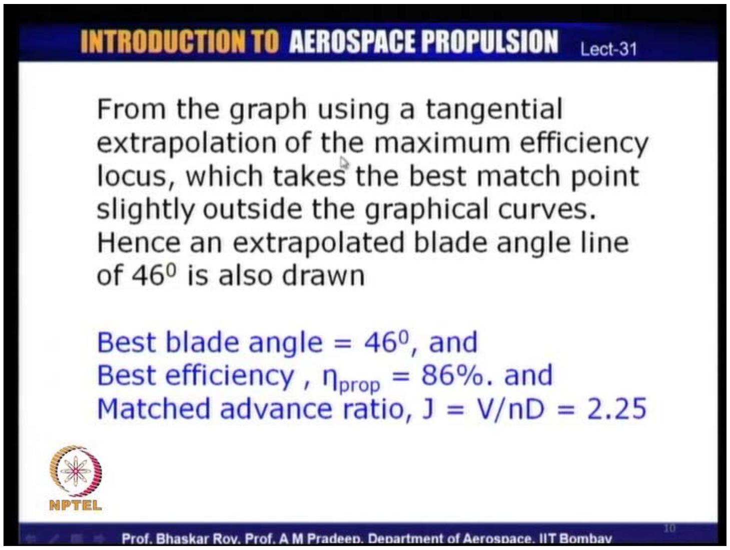

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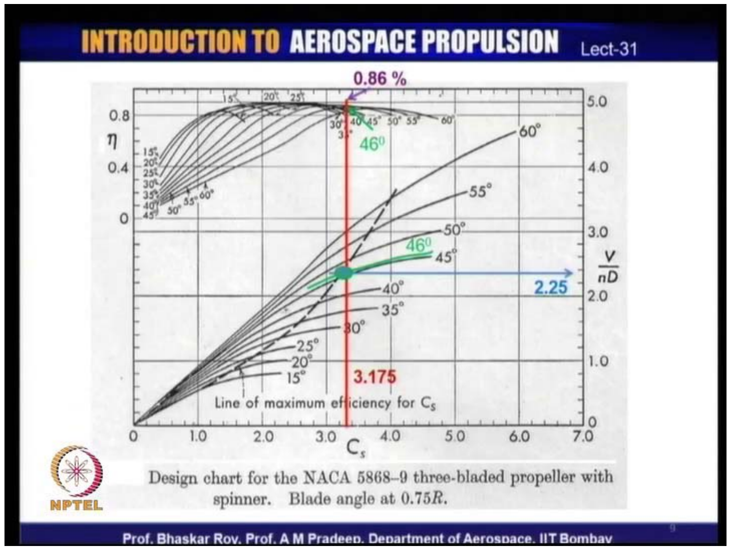

Let us proceed with this problem solving. We get the solutions which is let us say the best match point, and as a result of which, the extrapolated blade angle you can see that, it does not fall on one of the line; so, you need a slightly extrapolated line which is a 46 degree line. So, it is somewhere between 45 and 50 and close to 45. So, let us say the solution is 46 degree and the best efficiency for that 46 degree again we did not have a 46 degree efficiency line. So, that needed to be created, and as a result of which, that extrapolated solution gives us best blade angle for the reference section of the propeller at 46 degree and corresponding based efficiency would be 86 percent representative of the entire propeller and the advance ratio there is 2.25.

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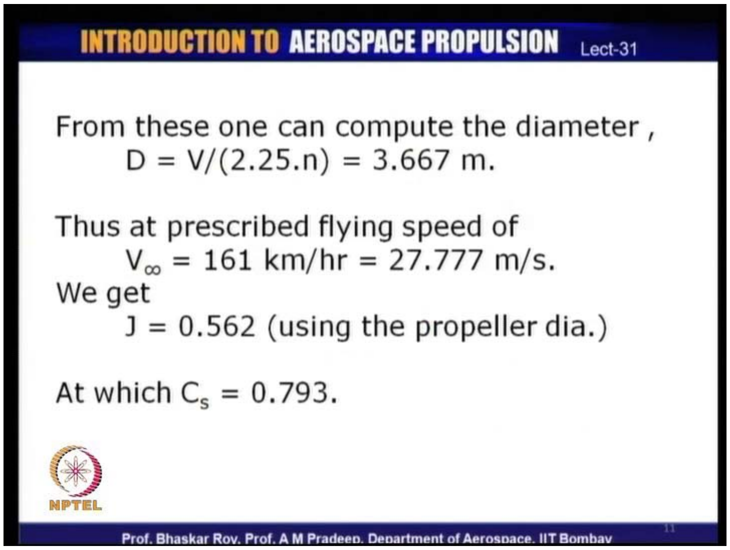

Let us proceed along this. From this, we can now compute that the diameter of this propeller based on these parameters would be 3.667 meters, and as a result of which, we get a value of J now. The velocity, forward velocity we had already calculated 27.77 meters per second as the alternative flying speed that was specified in the problem.

Now, we are solving the alternative flying speed, where it was specified as 161 kilometers per hour, a lower fly speed, and that, at that low fly speed, the forward velocity is 27.777 meters per second and there the advance ratio now is 0.562 given the value of D we have already found. Now, at this flying condition, the speed power coefficient C s would now be 0.793.

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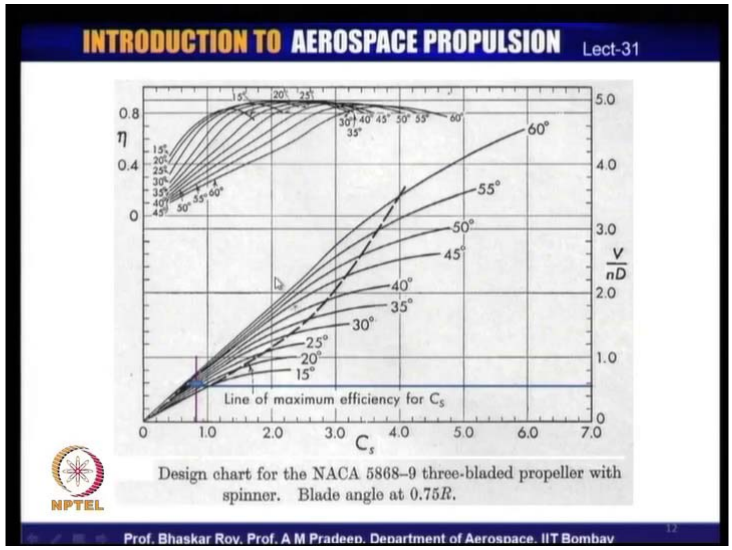

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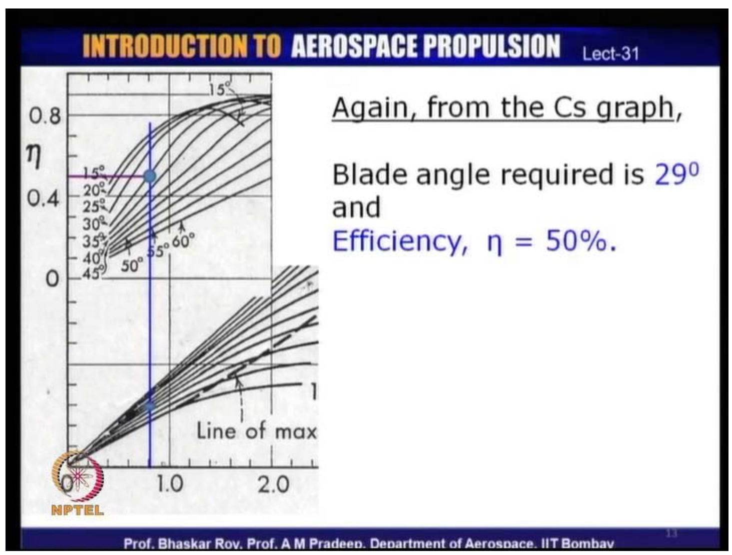

Now, you can use this value of advance ratio and this value of speed power coefficient to find a new solution and we use the graph again. What we see here that, we are now at a rather low speed power coefficient, a low flying condition, and at which, the advance ratio is also rather low and our solution point is somewhere over here.

So, this is what you get when you try to find a solution which is pretty close to the maximum efficiency operating condition of the particular propeller for which the characteristic is available to us, and as a result of this, we can conclude the solution by looking at that part of the graph a little more closely. This is where the solution point is and this is where we have arrived at as our solution and we get a blade angle is 29 degree, which is likely less than the 30 degree line which we have over here. That is the thirty degree line, and as we come along this at the C s of the value of that we have found. This is what the solution blade setting angle would be that is 29 degree.

Now, if you proceed along that and go to the 29 degree solution angle, you would get an efficiency - propeller efficiency - of 50 percent. Now, this is what you get from this map which is representative of this particular propeller, which is been designed and characteristic map created out of that design.

So, this is the solution of the alternative flying operating condition. That was specified in the problem where we get a blade setting angle now of 29 degree with an efficiency of 50 percent. So, when you are flying here, you should be at a blade setting angle of 29 degree with an efficiency of 50 percent. So, it can be seen that at this value of J which is representative of a low flying condition, the blade setting angle is 29 degree, where the efficiency is rather poor. It is only 50 percent efficiency which is a very low efficiency of operation.

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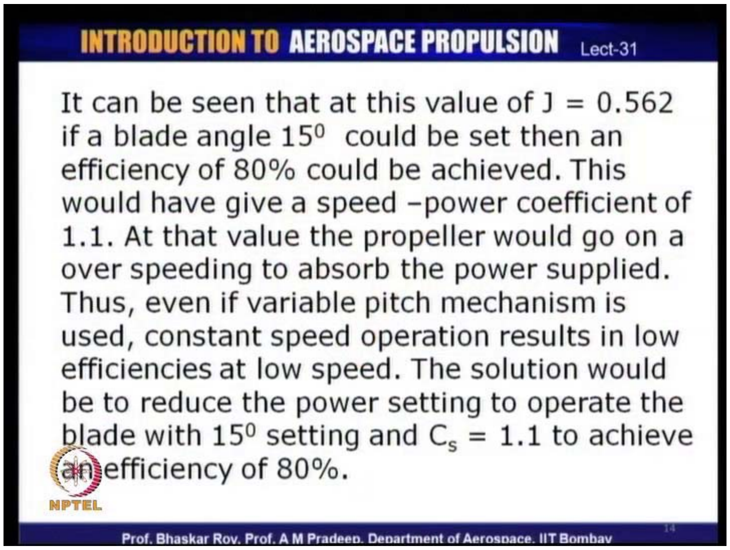

So, what can be done is - if you now set the blade setting at 15 degree, you could actually get an efficiency of 80 percent. Now, this is possible with this propeller only, and the blade setting angle could actually be used to get a higher efficiency and this would have given a speed power coefficient of 1.1.

Now, what happens is at that value, the propeller would go on an over speeding to absorb the power supplied. Now, you see, we had already specified the amount of power that is available, the gear box ratio that is available, and if we use those values as your input power and the result is that you would arrive at a situation where propeller is using propeller need is less than the power that is being supplied and this would result in an over speeding of the propeller; this over speeding of the propeller is not a good idea. The propeller would get hugely stressed due to the over speeding, and as a result of which, the propeller might break.

So, the problem statement, the alternative operating condition at low flying speed, then would require actually a variable pitch mechanism and this is where the variable pitch mechanism and its utility really comes in the variable pitch mechanism can now be used and you can now go outside the constant speed operation so that you can get a higher efficiency.

So, if you continue to use automatic variable pitch mechanism with constant speed, you would result in a low speed operation. You need to realize that the constant speed variable pitch mechanism which can go on automatic operation would result then in a low efficiency operation. So, you need to choose your operating controls rather judiciously. If you just leave it to automatic control as we see in this problem solution, you would result in a low efficiency propeller operation of the order of 50 percent efficiency.

On the other hand, what can be done in this particular operating condition is that you could actually choose a different speed of operation at which the power of the engine would actually be much lower. The propeller evidently does not need so much power anymore. It can do with much less power and you can choose a lower power setting, which means a lower speed of operation of the engine, and if you do that at that low speed, the power matching between the propeller and the engine would be more appropriate, and in that situation, you can now choose a blade setting angle of 15 degree at which the C s would be 1.1 and you can operate at an efficiency of 80 percent. So, you see, you can have variable pitch mechanism and you can keep the propeller operating at variable pitch. Normally, you would like to do that during cruise.

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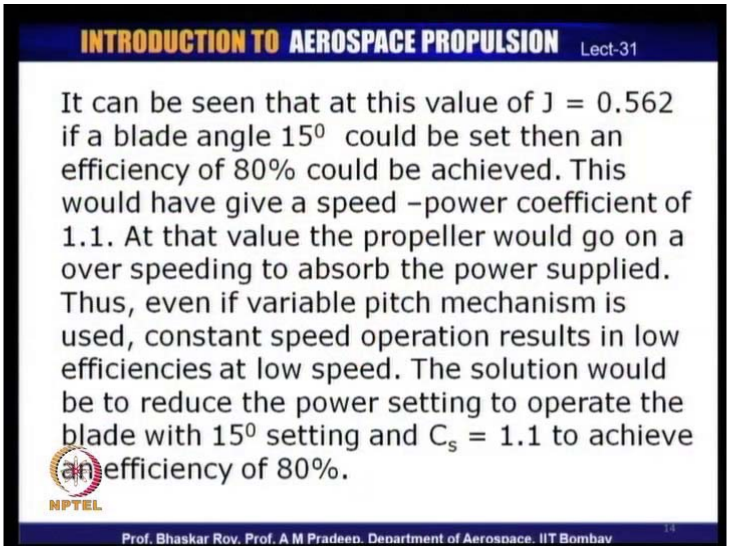

During cruise, you keep the propeller on automatic variable pitch constant speed operation and propeller would always have a what we call the floating pitch mechanism and it will set its pitch, but that is very good during cruise, whereas during low flying conditions, during very off design operating conditions, you would probably like to choose an engine operation of a lower speed so that the matching between propeller and the engine in terms of power matching also in terms of torque matching is more appropriate and there is no chance of the propeller over speeding to a very high speeds, which as I mentioned could result in the breakage of the propeller physical breakage of the propeller.

So, you need to and not to speak out the fact that it operates at a very low efficiency. So, the result is under certain operating condition as we see, it will be more judicious to go for a speed control, - control the speed at a lower speed of operation - and then, choose a propeller blade setting which now as we see can be a fine setting at which you get a good efficiency 80 percent efficiency of operation of the propeller.

So, the solution of this problem gives us a glimpse of the variable pitch mechanism which is used in most of the modern aircraft today and we see that the utility of the variable pitch mechanism indeed gives us a lot of handle in terms of operating efficiency of the propeller, but there is a certain amount of control logic that needs to be built in. So, not all the time the engine or the propeller needs to operate or should operate at a constant speed, and hence, the control algorithm or the control law that needs to govern the operation of the propeller and the engine together needs to be built in judiciously so that it continues to give very efficient operation during all modes of the aircraft flight.

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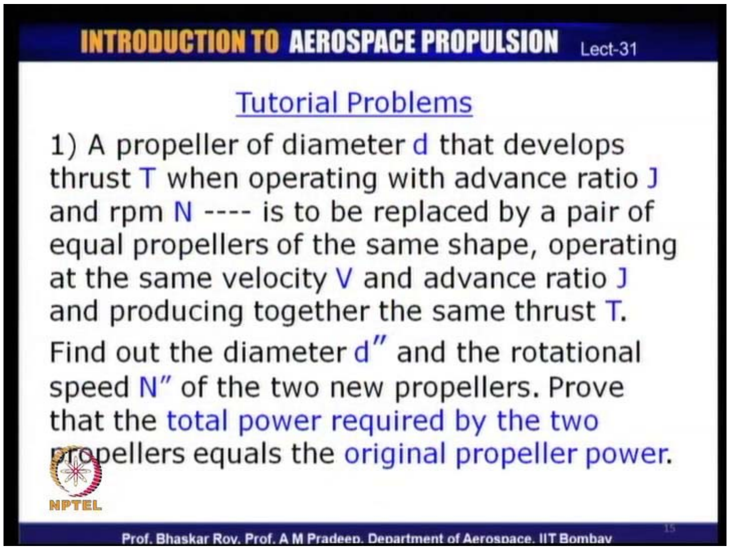

What I will do now is I will present to you now a few tutorial problem for your yourself to solve very simple problems so that you can make use of the theories that we have done in the course of this lecture series and apply those theories to the problem solving. I would say these are rather simple problems and should not have any difficulty in solving the problems. Wherever we have the problems which are numerical problems, the answers to the numericals are actually given. So, you can check you solutions and see whether you are arriving at the correct solutions, and as I mentioned, you should not have any difficulty solving these problems using the theories that we have done in the course of these lectures. So, these are the tutorial problems that I present to you. I will read out the problems to you 1 by 1. The first problem is propeller which has a diameter of d that develops thrust T when operating with advanced ratio J and rpm N.

Now, this propeller is to be replaced by a pair of equal propellers of the same shape, operating at the same velocity V and advance ratio J producing together the same amount of thrust T. So, the idea is to use two propellers obviously smaller in size, which would together would produce same amount of thrust operating at same advance ratio; that means an aircraft which was being earlier propelled by a single propeller is now being to be propelled by two smaller propellers, which have the same shape so that they produce the same amount of thrust.

The problem is find out the diameter d prime and the rotational speed N prime of the two new propellers which are obviously going to be smaller propellers and prove that the total power required by the two propellers equals the original propeller power, and if that is so, if that is so, you can use the same engine probably to use two propellers or you can use two smaller engines which together produce the same power. So, it is a very simple problem and you should not have any difficulty solving this problem.

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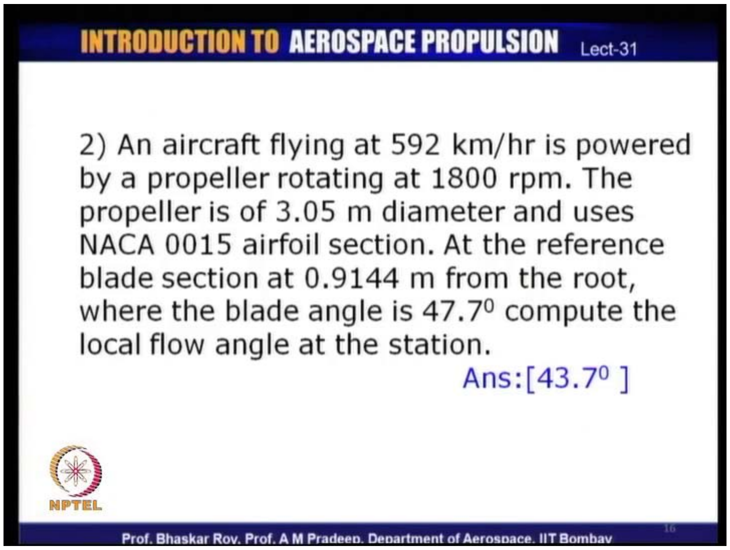

The second problem is an aircraft flying at 592 kilometers per hour is powered by a propeller rotating at 1800 rpm. That is fairly common rotational speeds of propeller, somewhere between 1200 to 1800 are normal propeller rotating speeds. The propeller is of diameter 3.05 meter and uses NACA 0015 aerofoil section, which are very standard old NACA aerofoils. At the reference blade section at 0.9144 meters from the root, the blade angle is 47.7 degree. Compute the local flow angle at that station, again a very simple problem. So, if you use the simple fundamental things that we have done, you should not have any difficulty finding the local flow angle. The answer is given here and that will also tell you what the local incidence is of that particular blade setting. So, this is again very simple problem.

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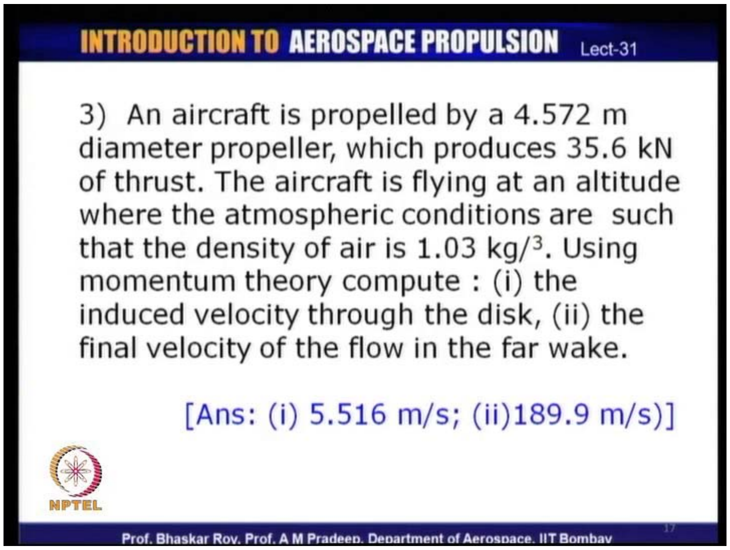

The third problem is an aircraft is propelled by 4.572 meter diameter propeller, which produces 35.6 kilo Newton's of thrust. A thrust as we see now would be expressed in terms of kilo Newton's for most of the aircraft engines, including propellers and all jet engines.

Now, this aircraft is flying at an altitude where the atmospheric conditions are such that the density of air is 1.03 kilograms per meter cube. Using momentum theory, compute the induced velocity through the disk. Induce velocity is the small v which we have done during the momentum or the actuator disk theory, and the final velocity of the flow in the far wake which is far downstream of the actuator disk of the propeller in the momentum theory and the answers are given here.

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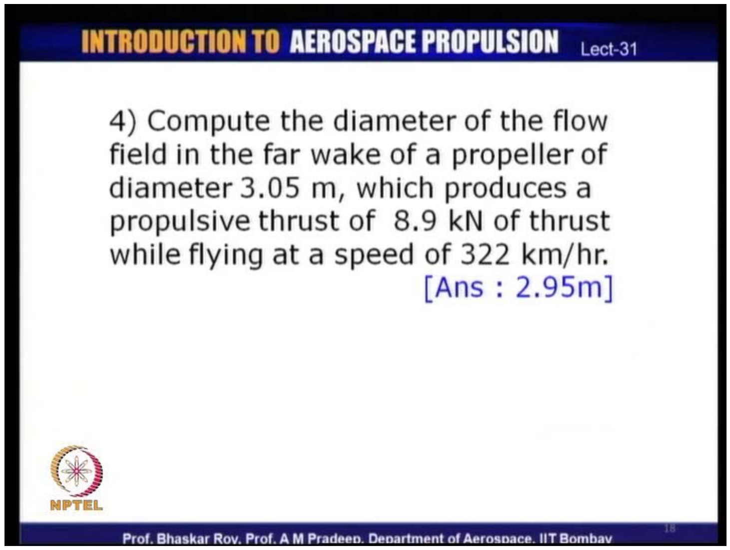

The fourth problem is the compute the diameter of the flow field in the far wake of a propeller of a diameter 3.05; that means the propeller has a diameter of 3.05 and it is producing a thrust of 8.9 kilo Newton's while flying at a speed of 322 kilometers per hour. What would be the diameter of the flow field in the far wake of a propeller? So, that is the problem statement which is given here should be able to find from the propeller theories that we have done.

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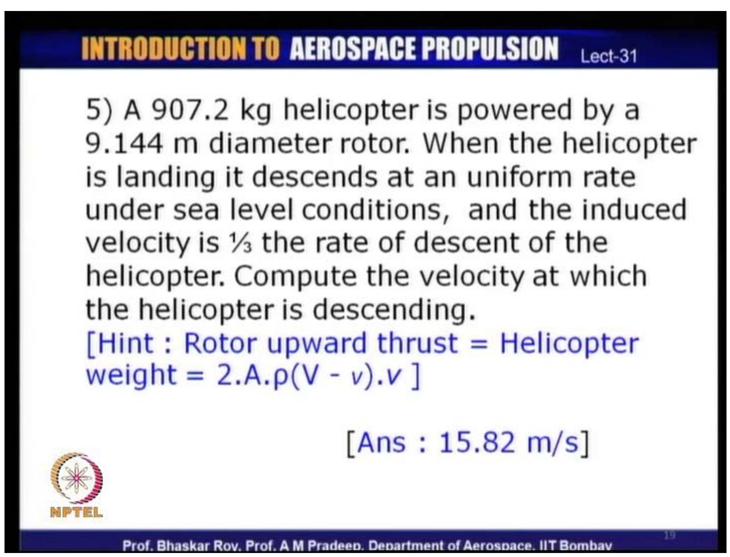

The last problem that I present to you is a 907.2 kg helicopter is powered by 9.144 meter diameter rotor which is as we know is very similar to actually a propeller. So, propeller theory applies there quite largely, and when this helicopter is landing, it descends at an uniform rate under the sea level conditions and the induced velocity small v as we have done in the momentum theory is one-third of the rate of descent of the helicopter. Compute the velocity at which the helicopter is descending.

A hint is given here for your solution that the rotor upward thrust is equal to the helicopter weight and the helicopter weight is given here. So, you should be able to use the momentum theory now to compute the solution of this problem; the answer is given here.

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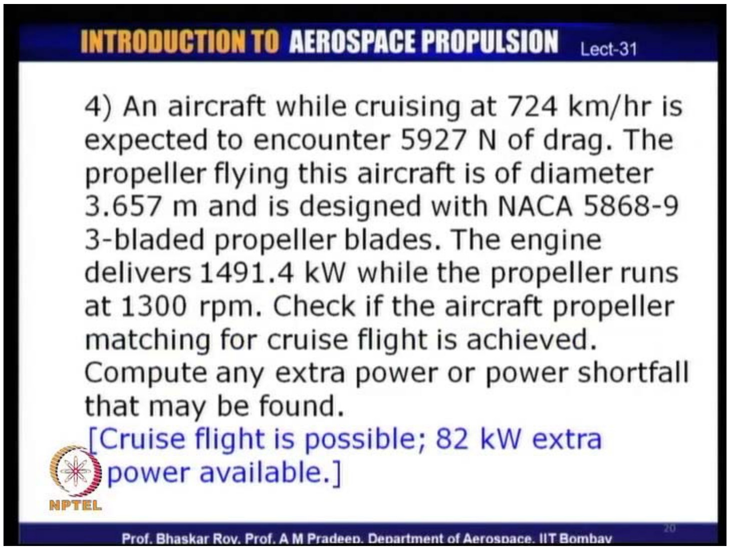

The sixth problem that we have is an aircraft while cruising at 724 kilometers per hour is expected to encounter 5927 Newton's of drag. The propeller flying this aircraft is of diameter 3.657 meters and is designed with NACA 5868 dash 9 3-bladed propeller blades of which we have done the characteristics before in the lecture. The engine delivers 1491.4 kilo Watts while the propeller runs at 1300 rpm very similar to the problem that we have solved, and check if the aircraft propeller is matched for the cruise flight and compute any extra power or power shortfall that may be found. So, you got to check whether the cruise flight is possible and whether there is any power shortfall the answer is given here and you can check your solution with the answers that are given here.

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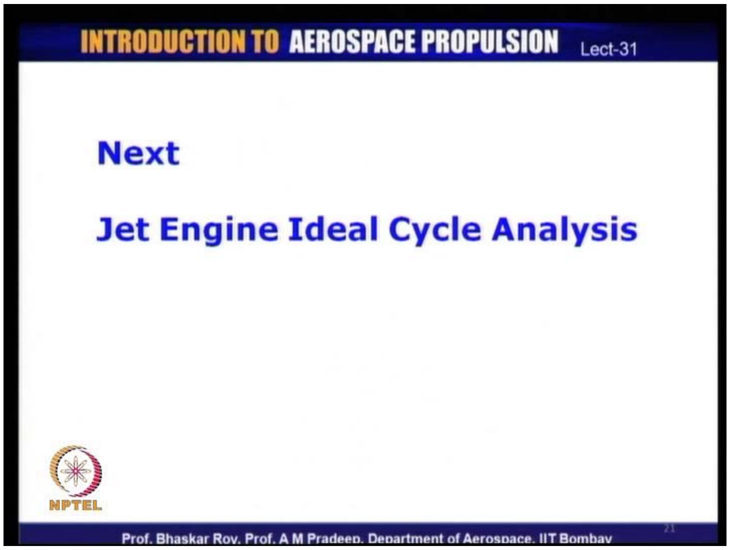

So, these are the few problems that you may like to solve by yourself and check out that the theories that we have done actually lead to reasonable solution of very simple problems that are available in many of the text books.

So, this concludes our lecture series on propellers. Next, we shall be moving towards various jet engine ideal cycle analysis which will be done by professor Pradeep, and from propellers, we will move on to various jet engines, and later on, I will come back and I will present to you the engines which are used for rockets and missiles, and in glimpse at some of the engines that use for space craft's. So, rockets missiles space craft is what I will come back to you for. In between professor Pradeep will present to you the jet engines and the details of the jet engine cycle analysis.