Introduction to Aerospace Propulsion

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Module No. # 01

Lecture No. # 28

Propeller Fundamental

Today, we will start a new chapter on propellers. Propellers have been providing thrust for flight of aircraft, for little more than 100 years - 107 years to be exact. Ever since, Wright brothers flew their first aircraft, it is propellers, which have been providing thrust for flight of aircraft.

The creation of thrust by the propellers is done differently, than let us say compared to jet engines, which came much later. The propellers create thrust by virtue of rotation of blades. How the thrust is created by the rotating propellers is what we will discuss in today's lecture and in-subsequent lectures.

The propellers initially when they were flying, the aircraft were made of wood - ordinary wood, because that was the material that was most suitable for giving the complex shape of the blades that the propellers are made of. Later on, over the years, new materials have given in, materials like aluminum alloys, materials like titanium alloys. Of late, the composites have given rise to more intricate and more accurate shaping of the propeller blades that has enhanced the efficiency of the propellers and allow propellers now to go to high speed applications. In fact, today, some of the modern propellers are working under supersonic and transonic working conditions.

That is the advancements that happened over a period of almost 100 years. To begin with the propellers, where made of very simple material, as I said wood, as a result of which, the shapes were also rather simple. Let us start with the fundamental issues that govern how a propeller works.

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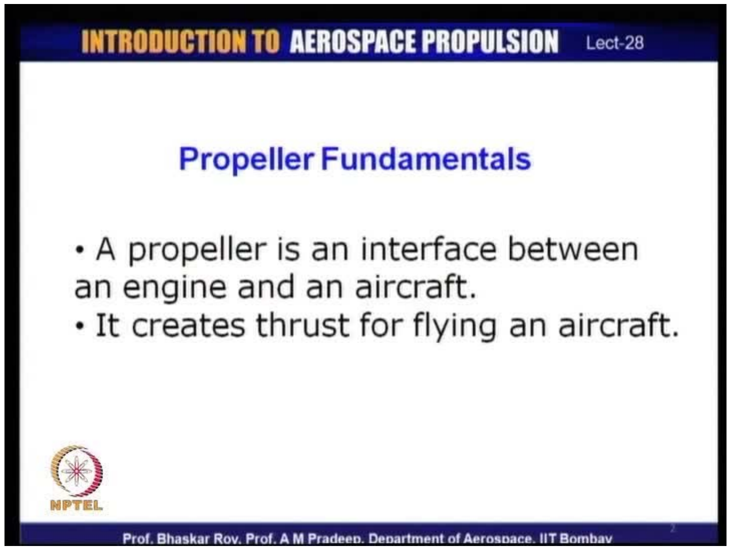

To begin with, a propeller is an interface between an aircraft engine and an aircraft. You see the engine, which we have been discussing; for example, in the last few classes, the piston engine, IC engines, they do not give you thrust, they actually provide only power. This power needs to be harnessed for creating thrust, which only then makes the aircraft fly. So, the aircraft requires thrust to fly. The propeller is the intermediary between the engine and the aircraft, for creation of thrust.

As we have discussed, this thrust creation needs to done differently during different modes of the aircraft flight; for example, when the aircraft is taking off, you need one kind of thrust or one amount of thrust. When it is cruising, you need another kind of thrust, another amount of thrust. All these need to be provided by the propeller during the various modes of the flight. So, the engine and the propeller need to be matched in a manner that will enable the aircraft to fly during its various flight modes.

The creation of thrust for flying of an aircraft is what the propeller is mainly entrusted with. So, let us see what kind of propellers people have been using over the years.

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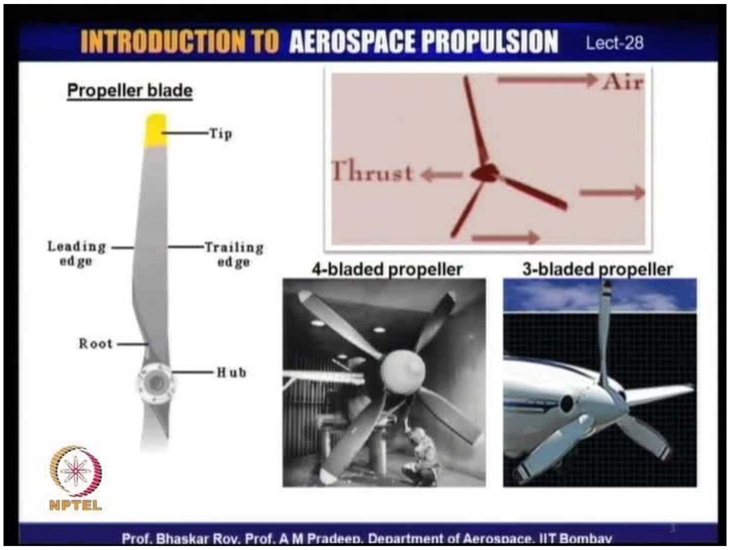

For example, propellers create thrust essentially by harnessing the air, which is available in the atmosphere. So, propeller works in the open atmosphere unlike an engine, which works inside an enclosed atmosphere, in an enclosed chamber of an engine. Whereas, the propeller is out in the open, it is working medium is the atmospheric air, the open air.

So, the air is deflected or rather pushed backwards by the propeller, this push backwards creates the thrust. The propellers over the years have changed their shape, size and number of propellers. We see here, in the picture, there are 3-bladed propellers and there are 4-bladed propellers. One could actually have 2-bladed propellers for very small aircraft, one seater or two seater, it is very small aircraft, or you can have propellers, which have up to 8 blades.

If the number of propellers blades is more than ten, in a propeller, the modern designers would prefer to call it profane, rather than propellers. They are propellers, which are counter rotating propellers, so we have two rows of 4-bladed propeller - let us say eight of them. The rear four is rotating in a direction - rotating direction counter to the front four, so that is a counter rotating propeller. Such very large propellers have been used in the past for flying very big aircraft in subsonic flight speeds.

So, some of these designs have been used over the years for creating maximum amount of thrust. We have also seen that the propellers actually are very efficient means of creating thrust. It is actually a more efficient device for creating thrust than a jet engine.

Because of this basic inherent efficiency of the thrust creation that propellers have held their ground, even today - even after 100 years. In fact, many of the very modern aircraft propulsive units that are coming up essentially using the concept of propellers for creating what are known as profanes. Essentially, they are modern versions of the earlier propellers, we will probably have a chance to look at those later on in this lectures.

Let us take a look at what a propeller details are, of a propeller blade. A typical propeller blade would have - what would be called as leading edge and what would be called as trailing edge. The root of the propeller is shaped in such a manner that it blends with the hub over here. Quite often the root may not have a proper shape for creating a thrust. Whereas, the tip of the propeller quite often is very thin, often may not make a very large contribution to the thrust creation.

We shall see very soon that the main portion, let us say from here to here, which actually are the main thrust creating part of the propeller, are made up of airfoil sections. So, propeller blades are essentially made up of airfoils, which invariably then participate in the creation of thrust. In this lecture, today, we shall see how that actually happens.

The propellers are finally rotating around central shaft, which is the hub of the engine and this shaft is getting power from the engine as necessitated by the actual propeller rotation. This matching between the propeller and the engine in terms of power is extremely important. We shall see today that this matching is required for power as well as for torque, which is also to be supplied by the engine. So, the matching of the power and torque is important for creation of appropriate amount of thrust, which then flies the aircraft.

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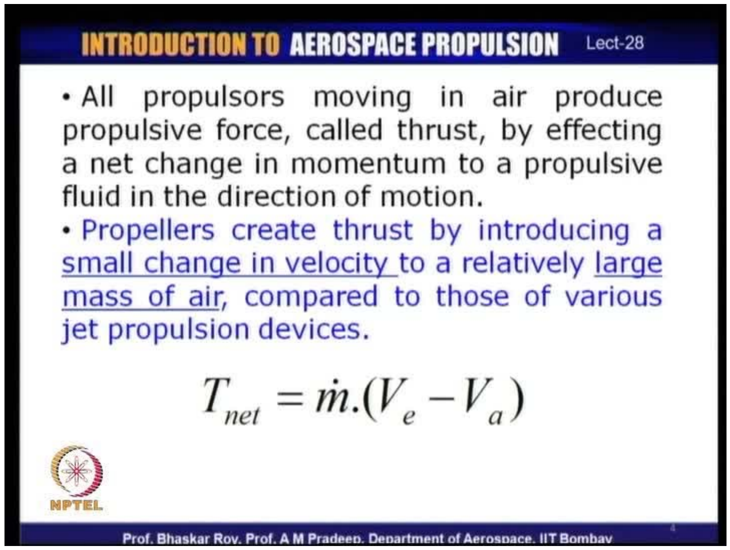

So, these are the some of the details that we will be going into in today's lecture. Let us look at the fundamental concept of how the propellers actually start creating thrust.

Propeller is fundamentally what can also be called a propulsor; a propulsor by definition creates thrust. The creation of thrust, the fundamental notion of creation of thrust is by making a small change in the momentum of the propulsive fluid, which in our case is air that has to be in the direction of motion and direction of motion of the aircraft. So, the direction in which the aircraft needs to move, in that direction, a net positive change in momentum needs to be created, which then creates the thrust.

Now, this is what a propulsor is supposed to do. The amount of thrust that is necessary is fundamentally dictated by the amount of the drag that the aircraft is experiencing. That is the minimum amount of thrust that the propulsor must create. If the aircraft is climbing or doing any other maneuver, then the thrustive part could be more. The propulsor is supposed to provide that additional thrust that is required for such maneuvers.

Now, again, fundamentally the propulsor creates thrust by changing the momentum. This is an equation, which you probably have seen before. In which, the thrust is equated to the mass of working medium, in our case air, which is taken from a velocity V a, which is the incoming velocity, let us say and the exit velocity V e. The differential of these two velocities multiplied by the mass of working medium essentially creates a thrust.

Now, in case of a propulsors or propellers, more specifically it works on the principle that the mass of air, it is activating, is very large. The amount of change in velocity is rather small compared to many of the jet propulsion units, which you may have already encountered.

So, in a typical jet propulsion, the mass of activation of air is comparatively much smaller, whereas the change in velocity is of a much higher order. Then, thereby, they create a sufficient amount of thrust for flying aircraft. In case of propeller, the mass of activation of air is very large; it takes a very small change in velocity to create sufficient thrust for flight of aircraft. So, there is a fundamental difference in the way propellers create thrust and how the jet propulsion devices create thrust, using basically same concept of creation of thrust.

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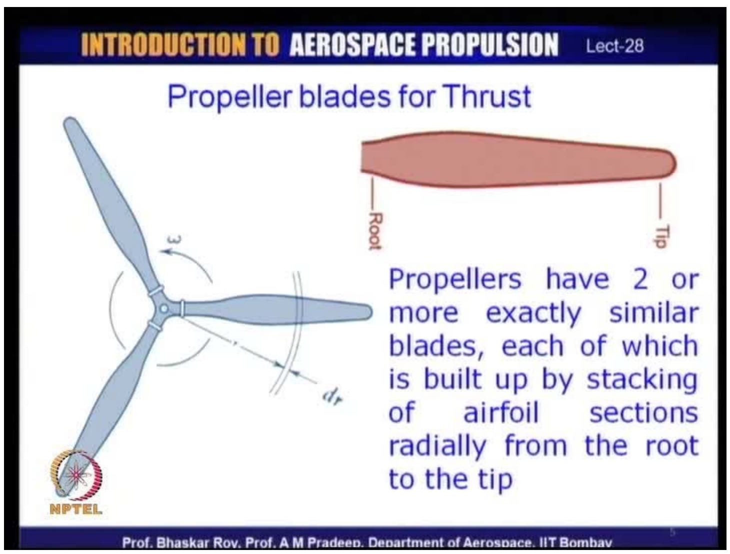

Let us take a look at the propeller blades, the modern propellers have many blades, but it can have minimum of two blades or more. Each blade is exactly similar to the other; they are set in a symmetrical fashion in annular space. So, you could have 3 or 4 or 6 or 8 blades, all arranged in a symmetrical fashion, in an annular space. Each of these blades is actually created by stacking of airfoil sections from root to the tip of the blade. So, the entire length of the blade is actually made up of airfoil sections.

What you see here in the picture is what can be called a plan form of the blade - typical propeller blade. In which, typically from the root to the tip of the blade, the size of the airfoil actually changes. The width of the propeller is approximately representative of the code of the airfoil. This width quite often in more popular way changes from root to tip, it is somewhat large in the middle section of the propeller, becomes somewhat lesser towards the tip. Quite often the tip is rounded essentially for reducing the losses related to the tip flow, the flow around the tip. The root is quite often a round kind of a section, could be almost a circular section, sacrificing all the airfoil shapes, essentially to provide good structural strength to the blade. Because, as you can see here, the entire blade is a cantilever, it is fixed only at the root. Rest of the blade, when in rotation, is actually a mold like a cantilever beam.

So, it experiences lot of bending forces over this entire length. The entire force and the moment have to be bound by the root section, which is fixed over here is also rotating. So, those sections are called often non aerodynamic sections, so they do not participate in the creation of thrust. Their basic job is to bear the stresses that are coming up due to the activation of the blades in rotation.

So, the shaping of the blades is done for various purposes. As I mentioned, the middle 60 to 70 to 80 percent of the blade, actually is aerodynamically shaped for creation of thrust. The root section essentially bears the load - the stresses; the tip section quite often rounded to ensure that the aerodynamic losses around the tip are minimum, so that the efficiency of the propeller is also maximized.

So, this is how normally a blade shape is created for propellers. We shall see later on in this lecture series that very modern blades often have somewhat different looking shapes, to cater, to the modern blade design and the modern aerodynamic thinking. We shall introduce those things as we go along in this lecture series.

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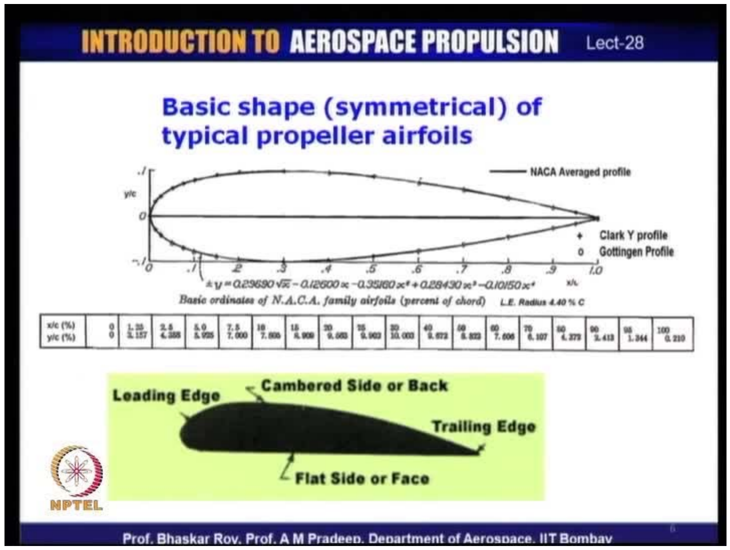

As I mentioned, the blades which are used in thrust creation are actually made up of airfoil shapes. If you take a sectional cut at any part of the blade, you will probably see an airfoil section. These airfoils have certain properties; as you probably know, these properties are harnessed essentially in a stack top manner to create the blades. All the blades together are then composition of airfoil sections, which are then together, creates the thrust. We shall see today how actually the blades finally create thrust, because as you all know blades fundamentally - their aerodynamic properties create lift and drag. We shall see today how this lift and drag are finally harnessed for creation of thrust.

What you see here today is a particular kind of airfoil, which has been created essentially as a basic airfoil shape for propellers. These blades are often designated by the creators; for example, some of the blades are known as the NACA airfoils, those are created by the American organization NACA more than 60 years back.

Some of the blades are known as Clark Y profile; some of them are known as Gottingen profile, which were created in Germany. These are the profiles which have been made, greatly used of in various propeller designs. The common feature in some of these profiles is that many of them actually have large part of one of the surface as a flat surface or what is often known as flat under surface. So, one of the surface is deliberately made rather flat, there is a rounding near - around the leading edge of a typical airfoil. Then you have that cambered side or the back of the propeller, which is then the main lift producing surface of this propeller. So, one of the surfaces is basically more of a non-lift producing surface, whereas the main lift production is left to one surface. This makes the job of the propeller designer a little easier and that is one of the reasons why these airfoils were created.

The airfoil always ends with a trailing edge, which normally has a very small rounding over here, much smaller than the leading edge rounding, typically much smaller, as a result of which, they create lift. The airfoil surface - as a result of the various frictional losses experience certain amount of drag, so that is a property of the airfoil. These properties are harnessed in the process of creation of thrust, in a rotating blade.

The co-ordinates of the NACA airfoil are given here, they are little small. I hope you would be able to sit down and look at those profile co-ordinates. However, these profiles are available in the open sources; you may be able to get them from various books and another literature, quite easily.

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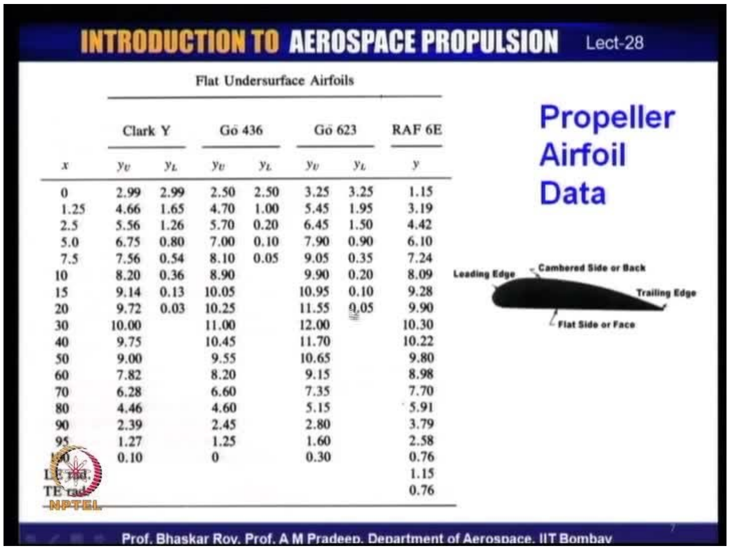

Flat Undersurface Airfoils

	Clark Y		Gö 436		Gö 623		RAF 6E
x	y_U	y_L	y_U	y_L	y_U	y_L	y
0	2.99	2.99	2.50	2.50	3.25	3.25	1.15
1.25	4.66	1.65	4.70	1.00	5.45	1.95	3.19
2.5	5.56	1.26	5.70	0.20	6.45	1.50	4.42
5.0	6.75	0.80	7.00	0.10	7.90	0.90	6.10
7.5	7.56	0.54	8.10	0.05	9.05	0.35	7.24
10	8.20	0.36	8.90		9.90	0.20	8.09
15	9.14	0.13	10.05		10.95	0.10	9.28
20	9.72	0.03	10.25		11.55	0.05	9.90
30	10.00		11.00		12.00		10.30
40	9.75		10.45		11.70		10.22
50	9.00		9.55		10.65		9.80
60	7.82		8.20		9.15		8.98
70	6.28		6.60		7.35		7.70
80	4.46		4.60		5.15		5.91
90	2.39		2.45		2.80		3.79
95	1.27		1.25		1.60		2.58
100	0.10		0		0.30		0.76
LE rad.							1.15
TE rad.							0.76

The other profiles which I was talking about, the Clark Y and Gottingen airfoil. The forth one is RAF, which is royal air force, airfoil given here. I hope you would be able to look at these profiles and create your own airfoils. These profiles are also easily available in open literature, in many books and other literature. All of these profiles given here have a common feature that all of them are flat under surface airfoils, as shown here.

So, those are the airfoil, which have been used for many years, for creation of propellers, which are mainly subsonic propellers. But, many of the modern propellers are transonic and very high subsonic, those airfoil are likely to be quite different from these airfoils which are given here. These are the standard airfoils used for somewhat low speed applications and they have been used for little more than 100 years. Now, we will look at the modern airfoils later on in this lecture series.

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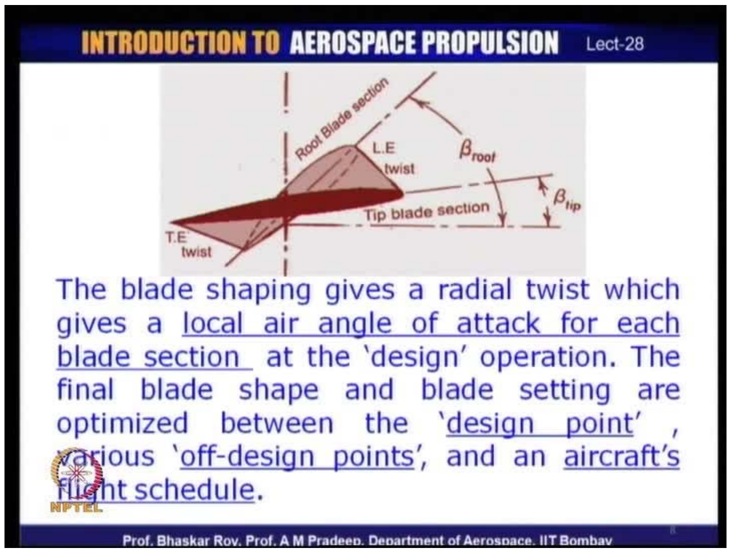

Let us see how airfoils actually are stacked in a blade. Typically when a blade is operational, the lift creation depends on the way the flow is locally incident on the airfoil. It depends on the airfoil characteristic, which is often decided by the local angle of attack.

So, what is shown here; for example, in this is that at the root section of the blade, it is subtending a very high angle of blade setting and this angle of setting is necessary for the root blade section. We shall have a look at the velocity diagrams in a few minutes - now.

On the other hand, near the tip of the blade section, it is set at a low angle. So, this is often called fine angle, this often called the course angle. As a result of this, necessity of tip being at a fine angle and the root being at a somewhat course angle, inevitably the blade gets a twisted shape. That is the amount of twist, which the blade would invariably have. Now, this would depend on the particular profiler design and it will vary from one propeller to another, it also depends on what it is being designed for.

Quite often the propellers may like to optimize the blade shape keeping in mind the various aircraft operations, which are often given in terms of so called design point. Various off design points, which cater to various aircraft flight schedules or various aircraft maneuvers, are required for the aircraft.

So, quite often the propeller blade shape could be some kind of an optimized blade shape. Finally, it is given certain amount of twist to cater, to all kinds of necessities that the propeller would have, to bear during its operation for creation of thrust.

So, a propeller not only is a composition of various airfoils, the airfoils are stacked at various angles of setting and that gives rise to the twisted blades, which are invariably the shape of each and every blade that are part of the propeller.

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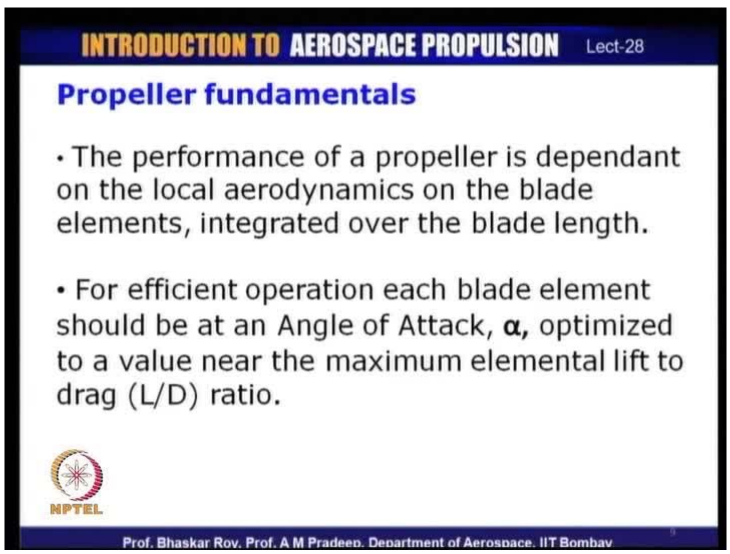

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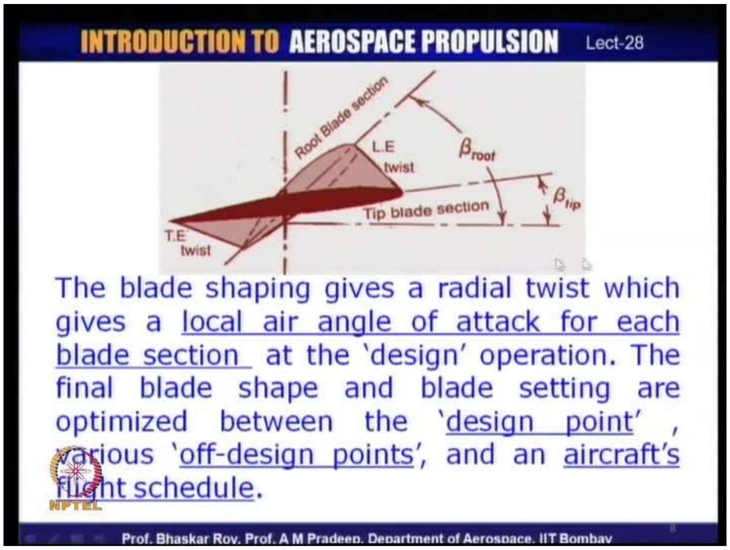

So, what we see now is that a propeller is typically dependent on the local aerodynamics of the flow incident on the blade elements. These blade elements are stacked, as we have just seen from root to the tip of the blade. This root to tip stacking essentially creates local flow incidents at various stations or various sections of the blade. The flow incident at the root, as we have seen in the earlier picture, is likely to be at this angle, whereas the local flow incident at the tip is likely to be at this angle.

So, the blade setting is actually given to the particular blade section, because the incoming flow or the relative flow angle would be actually around this angle at the root and around this angle near the tip. So, to meet the incoming flow incident on to the blade section, the blade sections are provided with the particular blade setting.

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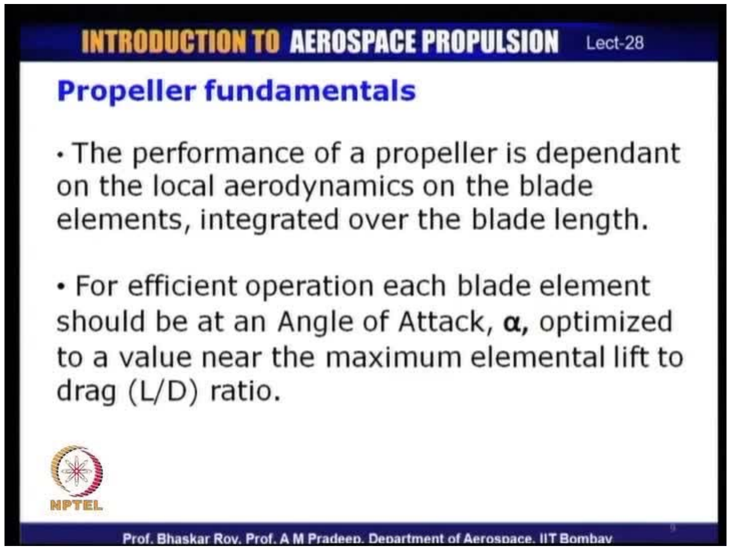

For efficient operation of each of these blade elements, which are airfoils, as we have seen, we need to create an appropriate angle of attack. As we know, all airfoils have a characterized value of angle of attack, at which, it is most efficient. It has a zone of angle of attack or a range of angle of attack, over which the airfoils are actually operative and they give good performance over this range, but beyond these range, the airfoils often likely to give very bad performance.

There is maximum angle of attack, where this airfoil is likely to stall; that means, it will simply refuse to create anymore lift and the drag would be too high. So, these ranges of angles of attack for each of these airfoil sections would have to be facted in, for each of these blade sections, which are stacked in creation for of the entire blade.

We have to see that if possible, most of the sections or as many of the sections as possible should operate somewhere near its maximum lift creating angle of attack. Or more appropriately, the maximum elemental lifts to drag ratio of each of these blade sections; that is what the designer has to do. Stack the blades in a manner that most of the blade sections operate somewhere near their individual maximum elemental lift to drag ratio.

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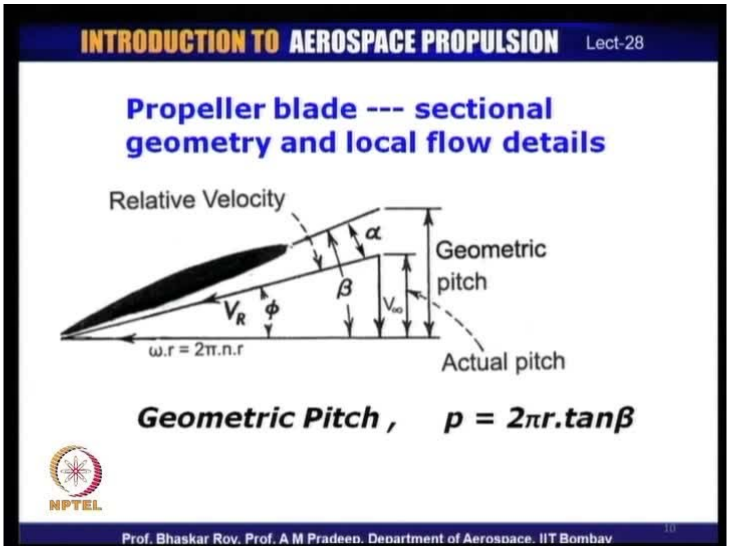

Now, let us take a look at a typical propeller blade, its sectional geometry and the local flow details. You see the sectional geometry, as is shown here, is fundamentally often airfoil section. What happens is you have a propeller, which is rotating. The rotation provides a certain rotational speed of the particular blade section, so each blade section is now rotating at a particular rotational speed or what may also be called a tangential velocity, which is omega r. Omega being the angular velocity, which can also be expressed in terms of twice pi nr. n being the rpm or rps of the blade that is rotating in a solid body, r is the radius of the particular section from the axis of rotation of the propeller. So, this provides a sectional rotational speed or tangential velocity of that particular section, with which it is now rotating.

Now, if the aircraft is moving forward and if the propeller together with the aircraft is moving forward, it has a forward velocity, which we may now call V infinity, which is the entire forward velocity of the aircraft propeller combined. Now, with which, if they are moving, it creates an angle of phi between the two velocities - the rotational velocity and the forward velocity, then two of them together create this resultant velocity V R, which is now the relative incident flow on to this airfoil section.

This incident flow now creates an angle of attack of alpha with reference to this blade section, which is an airfoil section. So, this angle of attack is what we were talking about, this needs to be something which is within the characteristic property of the particular airfoil that we have chosen. So, this angle of alpha needs to be kept in mind while creating the propeller blade, because this angle of attack has a maximum - beyond which this airfoil will refuse to do any aerodynamic action of any use to us. Very low angles of attack or negative angles of attack also could start creating non-aerodynamic effects of the propeller, which are again of no use as far as creation of thrust is concerned.

Now, what happens is, by virtue of the geometry that has been created these propellers have, what can be called an ideal forward motion, which is created or built into the geometry of the propeller. So, if this is the angle at which the blade has been set, it is expected ideally or theoretically that the forward motion of the propeller would be so much per revolution of the blade. So, for one revolution of rotational motion of the blade, the forward motion would be so much and that is called the geometric pitch. So that is the ideal pitch of the motion of the propeller - forward motion of the propeller.

What happens quit often is, because of the fact that air is flowing over the blade - the real flow that flows over the blade, an certain amount of small angle of attack is created, the angle of attack and the final angle that is subtended by the actual velocities creates an actual pitch, which is a result of real flow aerodynamics over the blade. There is a small difference between this geometric pitch and an actual pitch; we shall be talking about this difference in a few minutes.

So, when a blade is operational, it has a certain ideal geometric feature, which is built into the airfoil shape of the particular blade section. It is given a shape and a blade setting, keeping in mind certain norms of its operation, certain aerodynamic properties that it has. Then, the real flow happens.

So, there is always a small difference between what actually happens and what it was ideally designed for that difference is in terms of the geometric pitch and the actual pitch. The geometric pitch is given in terms of twice pi r into tan beta, which is the angle at which the blade has been set. So that is the geometric pitch, which the blade is supposed to encounter in its forward motion per revolution of the propeller.

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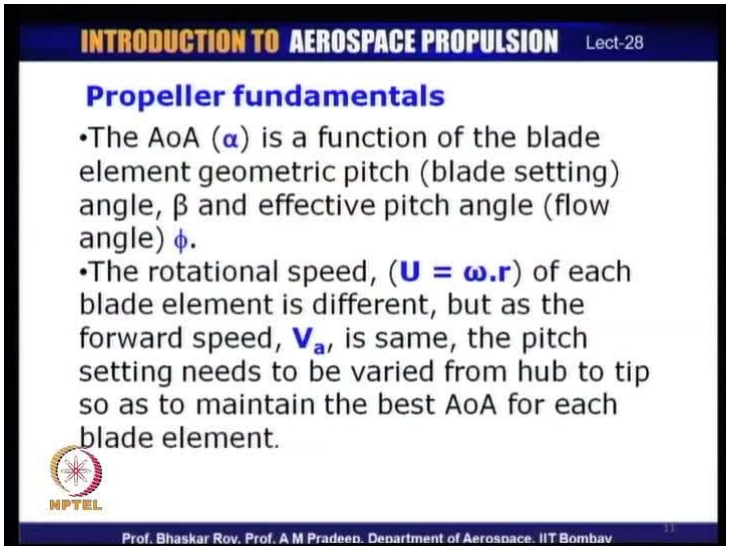

Now, angle of attack, which we are talking about, it is a property of the airfoil section, is a function of the blade element and the geometric pitch, which is the blade setting and which is built in to the design of the propeller, the effective pitch angle. So, these two things together create the angle of attack, which means the geometric pitch is something which is already designed, created and set. Let us assume, for the time being that it does not change; on the other hand, the effective pitch angle - the flow angle could change depending on the operation of the propeller.

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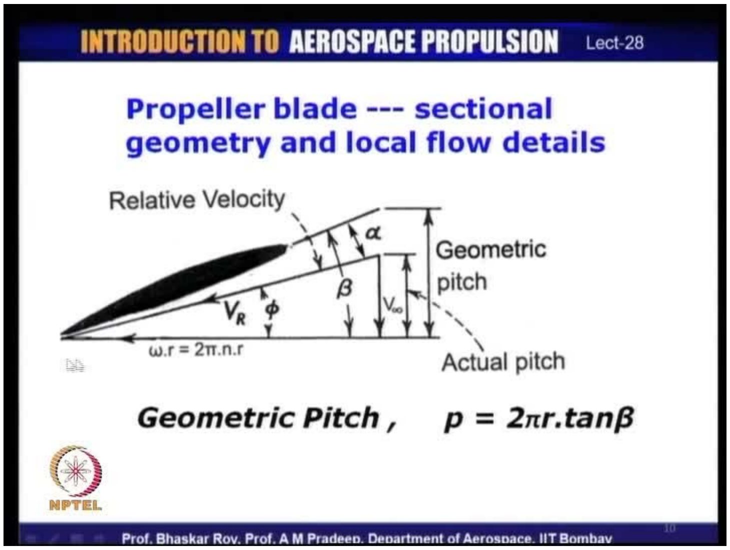

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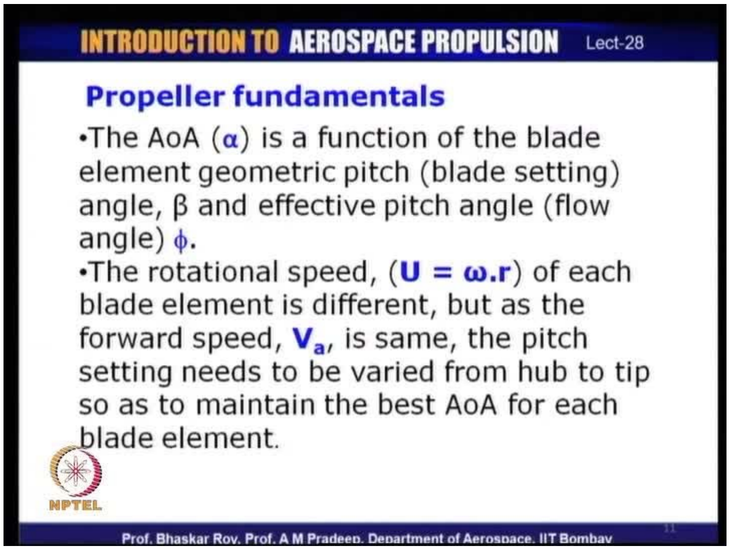

For example, if it is rotating at some other speed, this tangential velocity rotational speed would change. If the aircraft is moving with some other velocity - forward velocity, V infinity would change, in which case, this value of phi would change. Now, you see the beta has already fixed by design, for the time being, we are assuming that beta is not changeable, in which case, the difference between beta and phi that is angle of attack alpha would change. Now, this change occurs during the actual flight or operation of the propeller, as a result of which, the angle of attack is a variable quantity during the operation of the aircraft.

So, we have to keep an eye on this variation, see to it that it conforms to the airfoil properties, which has, as I mentioned, a range of angle of attack, within which, this airfoil is good, beyond that the airfoil is really not good for use as an aerodynamic entity.

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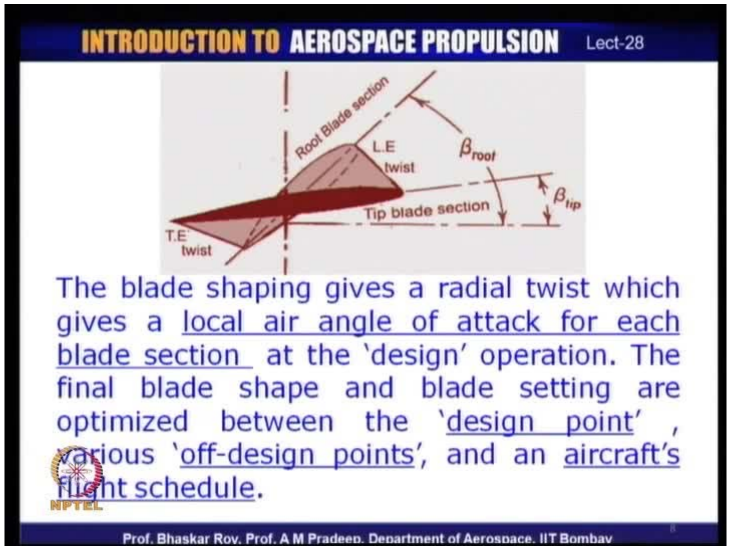

The rotational speed often designated as U, which is equal to omega r - of each blade element, it is different, it varies with r. Omega is fixed from for the entire blade, but the r varies from root to tip, hence that rotational speed would vary from root to tip. As the forward speed is let us say same from root to tip, the pitch setting needs to be varying from the hub to the tip.

So, as to maintain the best angle of attack for each of the blade elements, this is what gives rise to the twist. This is the reason because of which, we needed to have the blades at various angle of setting from root to tip. Because, the local rotational speed at the root is much less, the local rotational speed at the tip is much high, as a result of which, the angle required here, in fact, the value phi also here will be very low, so that we need to keep the angle of attack low over here.

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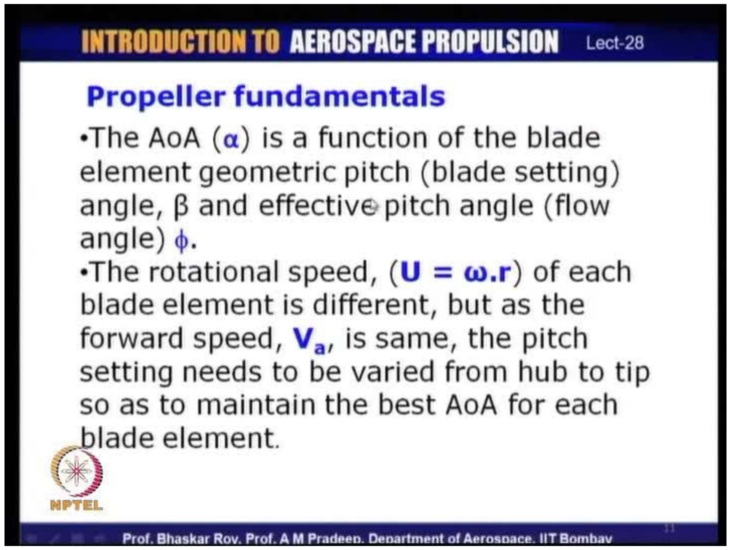

Whereas, in this case, for the root, the angle of attack also needs to be kept within in a certain value, but the value of phi here is going to be high. As a result of which, your blade needs to be given a twist. This is from the fundamental fact that the rotational speed omega is constant from root to tip, but the actual rotational speed that is U varies from root to tip - the tangential velocity varies from root to tip for each element of the blade.

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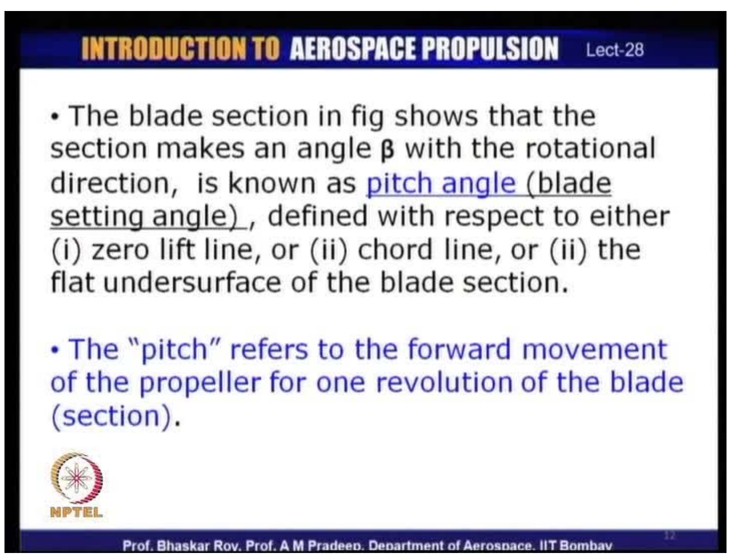

Thus the angle beta, which is made and that is what we are talking about, it is known often as the pitch angle or the blade setting angle. This is defined often with respect to either the 0 lift line of an airfoil or the chord line, which is more easily understood. Or in case of propeller, quite often the flat undersurface of the blade section, as we have just seen many of the propeller blades are indeed made up of flat undersurface airfoil sections. So, for propeller making that is quite often a very convenient reference line to which the blades could be set.

The pitch which we have just defined refers to the forward movement of the propeller for one revolution of the blade or the particular blade section.

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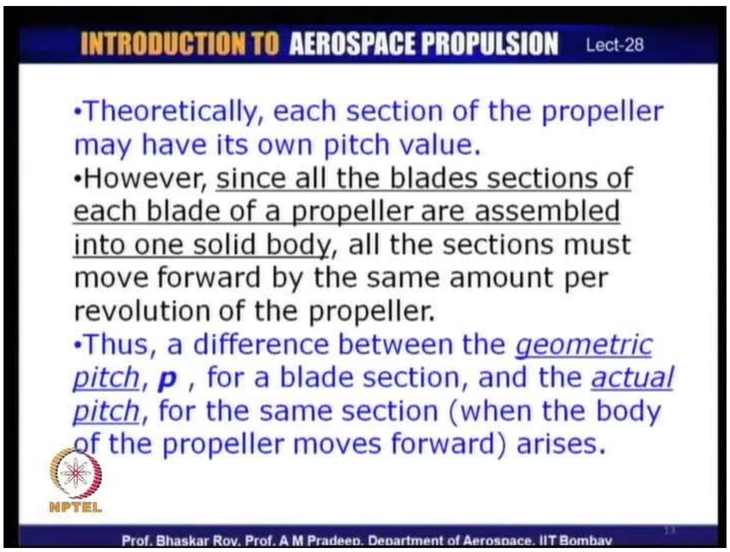

We shall see that theoretically. Each section of the propeller, as per the definition, we have just given, may have its own pitch, which is theoretically possible. However, you know that entire blade of the propeller is a solid body and hence the entire blade is moving together with all its blade sections and airfoil sections as one solid body. Hence, all of them have only one single forward motion, as a result of which, this difference between the geometric pitch and the actual pitch, which is for the entire blade, could be different for different sections. This difference arises as a propeller or the aircraft together starts moving.

So, the difference between geometric pitch and the actual pitch for the same section arises when the propeller starts moving, both rotating, as well as in forward motion. So, this is basically the concept of pitch, which needs to be understood with reference to the operation of the propeller. We shall see later on that this pitch as a concept has great importance in the operation of the propellers.

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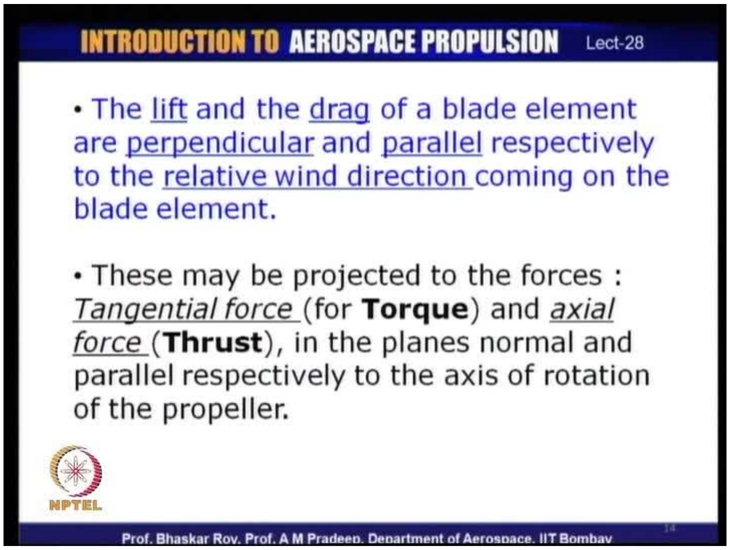

We are using airfoil sections for creation of the propeller blades. Airfoils fundamentally create lift and drag; they are fundamentally shaped to create lift and drag. Lift is the positive component, which we want; drag is the penalty you pay in the process of creation of lift.

So, these are the fundamental forces that are created by the blade shape. Typically the lift is perpendicular to the chord of the blade and drag is parallel to the relative wind direction coming on the blade element. The wind direction is often described with reference to the chord of the blade. So, these are the fundamental properties of the airfoil section, which is the blade element of the propellers.

What we shall see now is how these fundamental forces of lift and drag are harnessed towards creation of thrust and the tangential force, which is met by the supply of torque from the engine.

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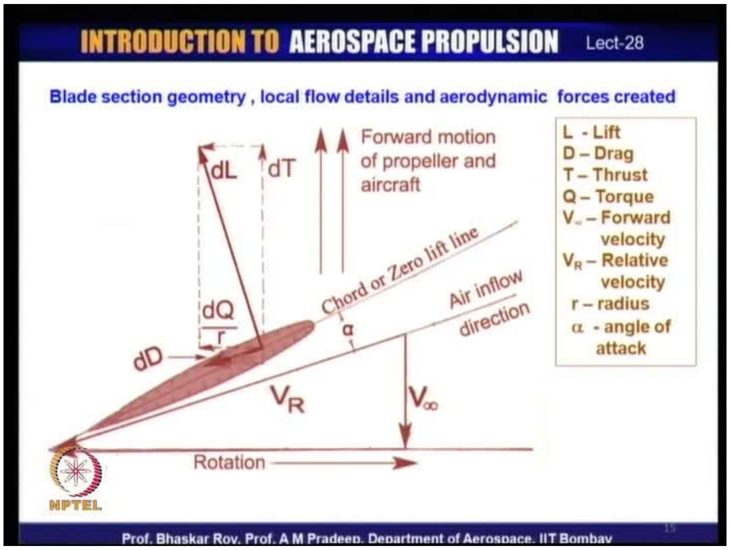

If you look at this picture, now you see that an airfoil is used here. Fundamentally for creation of lift a particular blade element being shown here. So, we are showing the lift in the form of dL - a small elemental lift let us say. So, L is lift, D is drag, T is the thrust, Q is the torque, V infinity is the forward velocity, V R is the relative velocity incident on this airfoil section, r is a radius at which this particular blade section is of the propeller. Alpha is the angle of attack, more specifically the local angle of attack for this particular blade section.

What we are showing here is the elemental values of lift and drag for this particular blade section. Hence, we are showing them as dL, dD, dT, etcetera to designate, they are elemental values for this particular blade section.

But, this particular blade section is now creating a lift over here and it is experiencing a drag. As I mentioned, drag is the penalty you pay in the process of creation of this lift. This is created by the shape of the propeller subtended at an angle alpha, which is the local angle of attack.

Now, if you decompose this lift and drag, which are perpendicular and parallel to the chord, if you decompose them in the form of axial force and the tangential force, which is dQ by r, what you get are elemental contribution to the thrust. So, dT is the elemental thrust of this particular blade section, dQ by r is the elemental tangential force, which has to be met by the supply of the torque from the engine.

So, this is the component that the engine needs to supply for creation of this thrust, through the shape of this propeller blade section, which is an airfoil section. So, this is the aerodynamic mechanism by which the thrust is created by the propellers, where airfoil shape is the fundamental element in the creation of thrust.

We had talked about various kinds of pitch settings from root to tip, however the pitch settings of the propeller as a whole can actually be defined in different ways depending on the operation which the propeller intended to have. The simplest of the pitch setting is what is known as fixed pitch propeller, where the propeller pitch from root to tip is fixed. It is not going to change during the flight of the aircraft; it is not changeable at all. This kind of propeller is what the Wright brother used to begin with when they started flying. It was being used in the early generation aircraft for many years, those blades, as I mentioned earlier, used to be made of wood. These fixed pitch propellers were also needed to be optimized as I mentioned, so that cater not only to the aircraft take off, the cater to the cruise and then later on to various maneuvers. So, these were the fixed pitch propellers, which were being used in the early days of aircraft flight.

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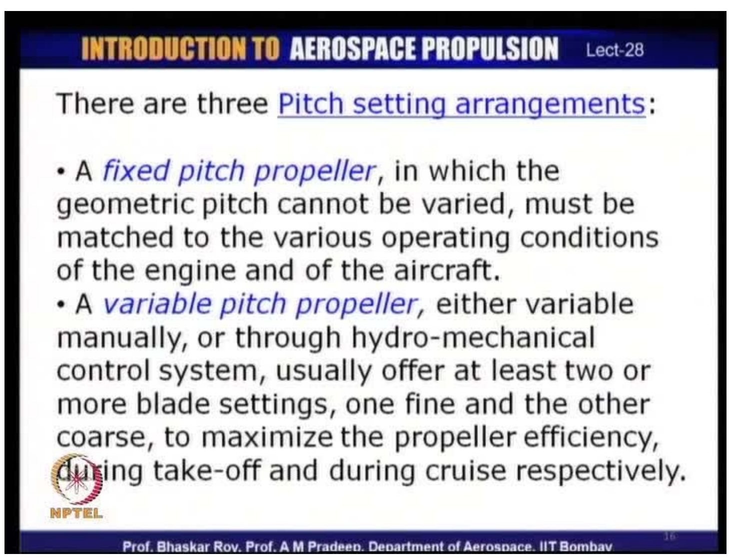

The variable pitch propeller which came a little later actually had the capacity to vary the pitch manually through variable mechanisms, which could be done on ground, during the ground servicing or through some hydro mechanical control system. This could be done also during flight by the pilot, he could fix a pitch depending on whether the aircraft is actually taking off or whether the aircraft is cruising and then it becomes a fixed pitch.

So, quite often they have 2 or 3 or 4 settings, sometimes it is the fine setting which is often used for takeoff and the other is often the coarse setting, which is often used during the cruise. So that at these respective flight modes, the propeller works at their maximum efficiency, which translated to the blade sections, means that the blade sections are now optimized at their best angle of attacks at the each of the sections during takeoff and cruise. So, this variable pitch setting propellers allows the propeller to work close to their good efficiency operation, as a result of which the propeller efficiency is much better during each section or each segment of the aircraft flight.

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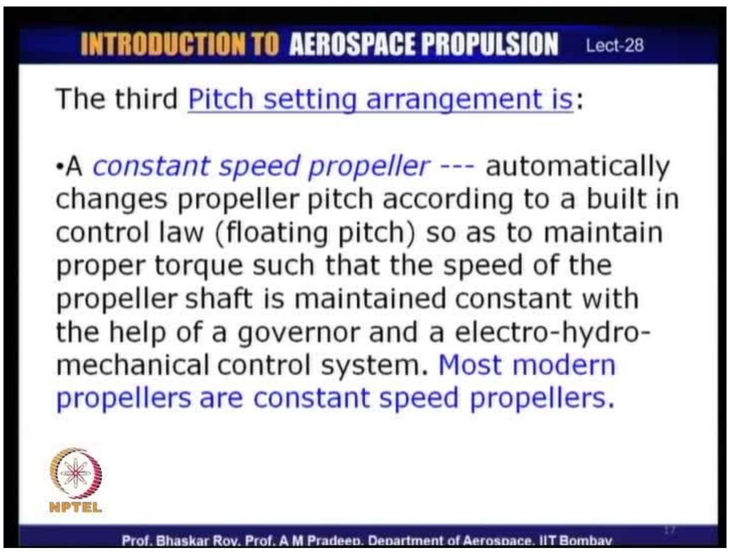

However, the most modern kind of pitch setting is referred to as constant speed propeller, which is often controlled by a control mechanism. The propeller pitch has a built-in control law, which is often also referred to as floating pitch. So, have to maintain torque balance between what the propeller needs at a particular time of operation and what the engine is supplying. This torque balance is extremely important during the entire operation of the propeller.

The speed of the propeller which is being supplied by the engine through the shaft is maintained constant during this operation. So, the pilot or the control system tries to maintain a constant speed, which is good for the engine, because the engine can supply a steady power supply at a constant speed. If you can keep it at a high speed, the engine can continue to supply at that high speed a good quantity of power.

On the other hand, the pitch is now set on a floating mode, the result of which is that it automatically sets itself to a good pitch setting so that the propeller efficiency is good or as high as possible. This is often an electro hydro mechanical control system, most of the modern day propellers do have this kind of control systems built in to the aircraft control system, which is simply called control constant speed propellers.

So, these kinds of propellers are being used in all the modern aircraft today, which allows the propeller to set its own pitch during actual flight. It sets its own best pitch for the best possible efficiency of the propeller, for that particular flight segment of the aircraft.

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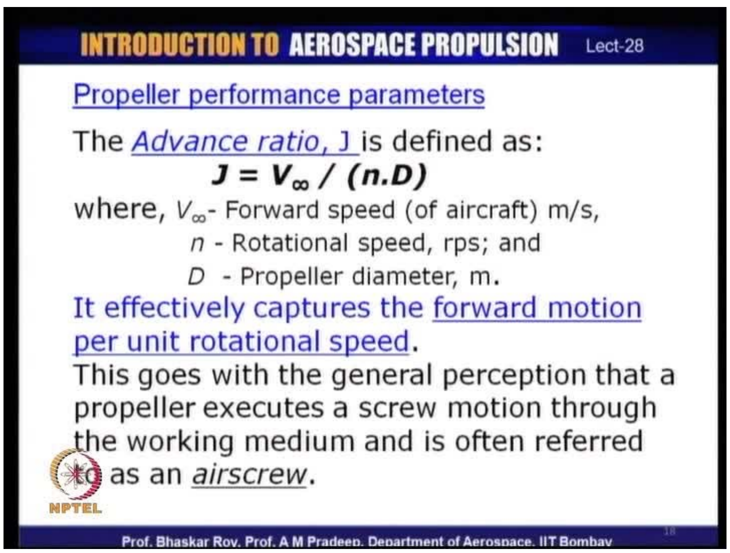

Let us try to take a look at some of the propeller performance parameters that are often used as figures of merit for the propeller. These performance parameters are the fundamental parameters by which a propeller is often specified or designated. The first parameter that is typical of a propeller is known as advance ratio. In most of the literature, it is designated as J at equal to V infinity divided by nD. n is the rotational speed of the propeller often expressed in rps and D is the propeller diameter, which is the tip diameter of the propeller, expressed often in meters.

Now, this advance ratio is a non-dimensional parameter, is often used to characterize the propeller. As you can see, from the definition, it will change with the forward speed; it will change with a rotational speed. So, if you change any of the two parameters, the diameter of the propeller let us say is fixed once a propeller is made. If you change any of the two operating parameters, the forward speed or the rotational speed, the advance ratio - J is going to change. Hence, the J is fundamental parameter by which the propeller needs to be characterized.

Now, the basic definition of J actually means that it is the forward motion of the propeller per unit rotational speed. Now, this brings in the fundamental concept that propeller is actually executing a screw motion through the working medium, which is air in some of the literature, or many of the literature, is often referred to as air screw. Hence, a propeller effectively is executing a screw motion as it is going through the air. This is what fundamentally propeller does when it is creating thrust, it is executing a screw motion through the air in the process of creation of thrust.

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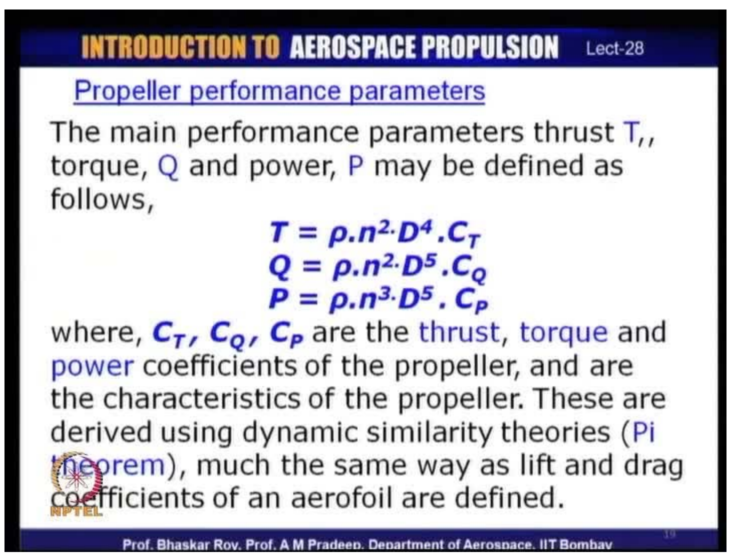

The other important characteristic parameters of a propeller are the thrust, which is what we need to fly the aircraft. The torque which is needed to be the supplied by the engine and the power needed to be supplied by the engine, so power and torque are the two quantities that need to be supplied by the engine. Thrust is what you get from the propeller shape by the rotation of the propeller and it is used for flying the aircraft. So, supply is P and Q, thrust is what you get by operation of the propeller.

Now, these parameters are often defined in terms of certain coefficients, which are as I mentioned is figures of merit of a particular propeller or a propeller shape. These are defined in terms of the density at which it is actually operating, the density of air, the rotational speed n, the diameter of the propeller D. C T, C Q and C P, which are three coefficients, which are characteristic of a particular propeller. These are called thrust coefficient, torque coefficient and power coefficient; these three coefficients together with advance ratio characterize the entire propeller. We shall have a look at these characteristics later on in the course of these lectures.

Now, these are what defined in terms of the fundamental parameters of the propeller, which are built into the size of the propeller, which is D, rho is the density of the air in which it is operating and n is the rotational speed. So, we get the three parameters which we need, P and Q which is to be supplied by the engine, thrust is what you need to fly the aircraft. How are these parameters of these particular coefficients created? They are created by using the dynamic similarity theories, often popularly known as the pi theorem.

These created much the same way as the lift coefficient, the drag coefficient and airfoil are defined; also you would remember the coefficients like Mach number, Reynolds number, these were all created by the same dynamic similarity theories. The same theories have been used to create these coefficients, which characterize the propeller. So, instead of C L and C D of an airfoil, we now have C T, C Q and C P of a propeller, which define the activities of a propeller. So, these are the characteristic parameter of a propeller, we shall have a look at the characteristic nature later on in the course of these lectures.

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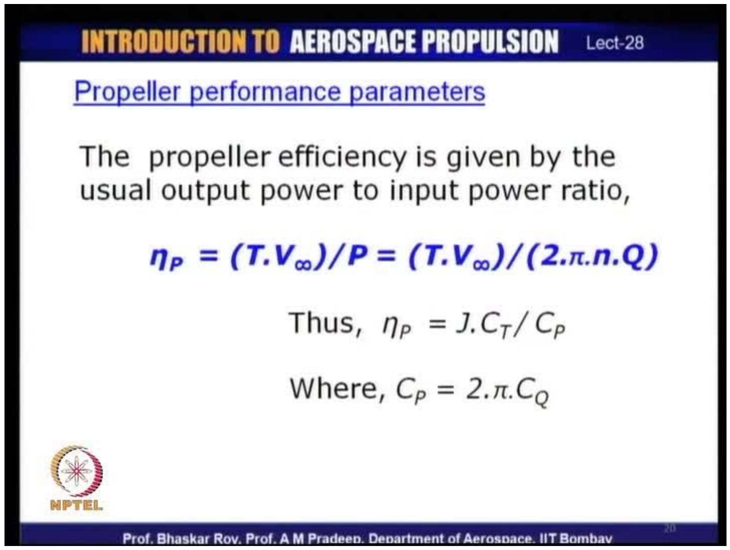

The propeller performance can also be given in terms of the efficiency of the propeller, which is also can be called the propulsive efficiency of this particular thrusting device. It is simply given in terms of the TV infinity, which is the thrust work being done by the propeller and P is the power that is being supplied by the engine. So, this is the efficiency of the propeller, which as I mentioned can also be called the propulsive efficiency of this propulsive device.

Now, using the definitions of the coefficient that we just seen, the propulsive efficiency or propeller efficiency can also be shown in terms of JC T by C P, J being the advanced ratio, C P can be written in terms of twice pi C Q. So, we can see that the efficiency of the propeller can be very quickly determined from the propeller characteristics, once we know what the characteristics are. These characteristic are often designated in terms of the advance ratio, which is operating at a point, which defines operating point of a particular propeller.

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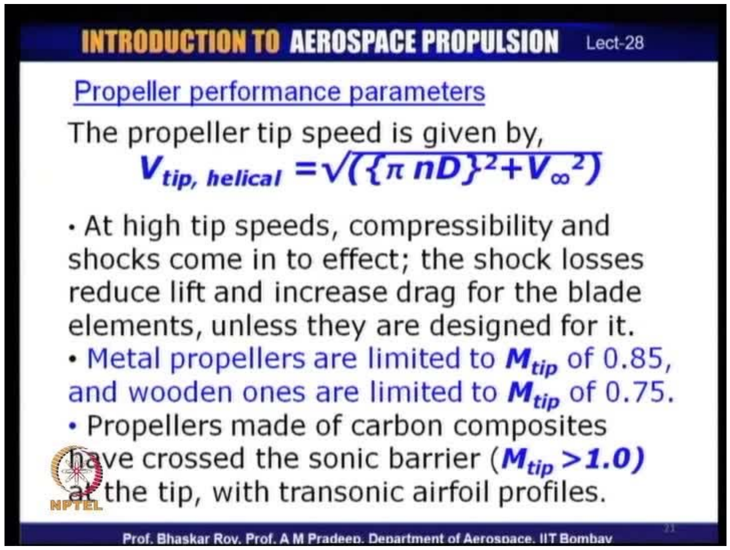

So, these are the basic definitions of a propeller performance. We have one more definition, which we can look at, which is the propeller tip speed. That is given in terms of the diameter, the rotating speed of the tip and the forward velocity with which it is moving forward. So, this is the rotational velocity of the tip of the propeller, this is the forward velocity of the propeller that gives the tip velocity, which it can also be called the helical velocity. Because, as we just discussed that the propeller is executing a helical screw motion through the air, hence the tip actually executes a helical motion through the air; hence the V tip actually is a helical speed.

Now, what happens is, this speed V tip, which is a combination of rotational speed and the forward velocity can experience compressibility and even shocks when the tip speeds goes very high. In the modern propellers, these tip speeds actually go very near the sonic values, if it crosses the sonic speed the Mach number 1, you could experience shock. Once we have shock, the shock losses come in to the picture, which you have studied in the earlier lectures. They will tell you that the shocks would reduce the efficiency of the propeller.

So that is exactly what happens if the propeller starts rotating at high speed. The propellers would experience tip speeds, which are supersonic and then you would have shocks. Those shocks would then reduce the efficiency of the propellers, the propellers could become of lower efficiency, which would tell on the fuel efficiency of the engine.

These shock losses are avoidable things as far as the conventional propellers are concerned. The conventional propellers, which earlier were being made of metal or even earlier of wood, had limitations of tip speed. For the wood it was of the order of 0.75 and for the metal they were of the order of 0.85.

However, the modern propellers are being made, which are made of carbon composites, these have actually crossed the sonic barrier. I will have occasion to show you some of these blade shapes later in the course of these lectures, where transonic airfoils have been used as airfoil profiles for the propeller blades. They are transonic propeller, which have been used in the modern propellers. They are made of carbon composites, where the shock losses by design can be kept to the minimum. You can still have a very good and very high efficiency propeller operating at very high speeds.

So, these are the various performance parameters that define how a propeller actually operates during the course of its operation, under various operating conditions. In the next lecture, we will have a look at the various propeller theories that are used in the propeller design. Those are used for analyzing the propeller and creating the propeller characteristics, which of the fundamental parameters, which we discussed today. These parameters would need to be characterized by design; these characteristics are to be then given to the propeller manufacturer and the propeller user for use of the propeller during the actual aircraft flight.

So, we will have a look at these theories over the course of next few lectures. We will see how these propeller fundamental parameters are characterized in what is known as characteristic plots of the propellers over the period of next two lectures.