Introduction to Helicopter Aerodynamics and Dynamics

Prof. Dr. C. Venkatesan

Department of Aerospace Engineering

Indian Institute of Technology, Kanpur

Lecture No. # 09

Now, I just want to mention because there were some questions last time, because I want to clarify, because the autorotation, when we mean by autorotation, it can happen in the sense, it is a particular condition, that condition is the power that is given to the rotor, is 0.

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So, the power to the rotor, if you say, that is, you can say, P shaft, this is what essentially the climb power. It is a climb velocity, this is the induced, then you have rho… This quantity very, very simplistically, only the, because this is refer to only the main rotor, because you say, this is climb induced, this is profile, they will be 0 at a particular descend velocity because this descend means, V is negative. V is negative means, this quantity can be made equal to 0 and that condition is called autorotation.

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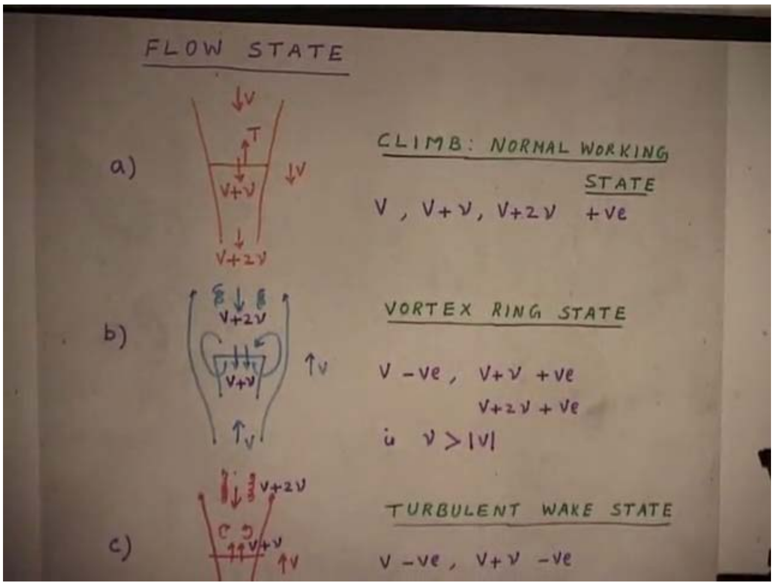

Please understand, because you may think, that these are all, this is a descend state, this is also descend, windmill break is also a descend state, everything is descend, descend, descend, but autorotation, when we mean, it is that particular state where the power required to rotate the rotor is basically 0. That is, engine has failed; engine is not supplying any power that is all, so, but yeah…

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No, no, you will have this also. See, you have a profile…

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In the graph, that is why, now you were asking, that graph is drawn, see you, only to indicate, see this is the graph you are talking about.

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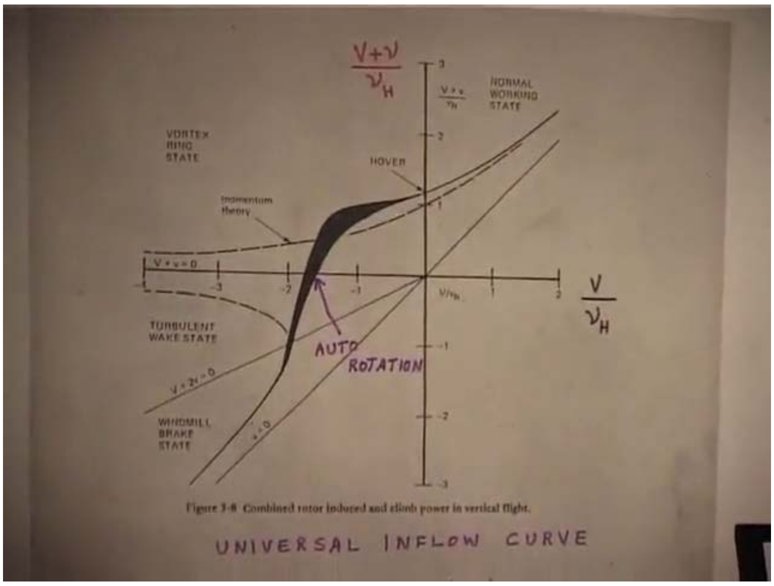

V plus nu 0 is this axis, essentially. Yes, it is close to autorotation because if you neglect this term, that means, the profile drag, I am not including only the induced power because usually, the induced power is much larger, you understand. This is not very large, but it is there, that is why, the real operation to mathematical, just an ideal definition for autorotation, simply say, V plus nu 0 is autorotation because you are considering only induced power, you are not considering all the other power. If you really consider everything, you may have the tail rotor, also may require and then, there could be some transmission losses and then the fuselage drag also can be there.

So, there can be several other factors contributing to the power of engine, which have to be supplied to the rotor, but we are basically not including those. In the real life, it may not happen at V plus nu 0, it will happen a little down, T plus nu, a little lower. Because even if you include this, V plus nu is not 0, V plus nu is equal to this quantity, you understand, that is why, autorotation happens at a descend velocity slightly greater than in the one, that meets the V plus nu line, it is 0 value, that is, from real calculations.

Because there was a question last time, where will it auto rotate? Here also it will generate power, but that condition you do not call it autorotation, is it clear? Now, let us look at the, is it, there are some interesting physics associated with this autorotation, I thought I will briefly explain that part today and then see, one is the, the easiest because this is very important for you.

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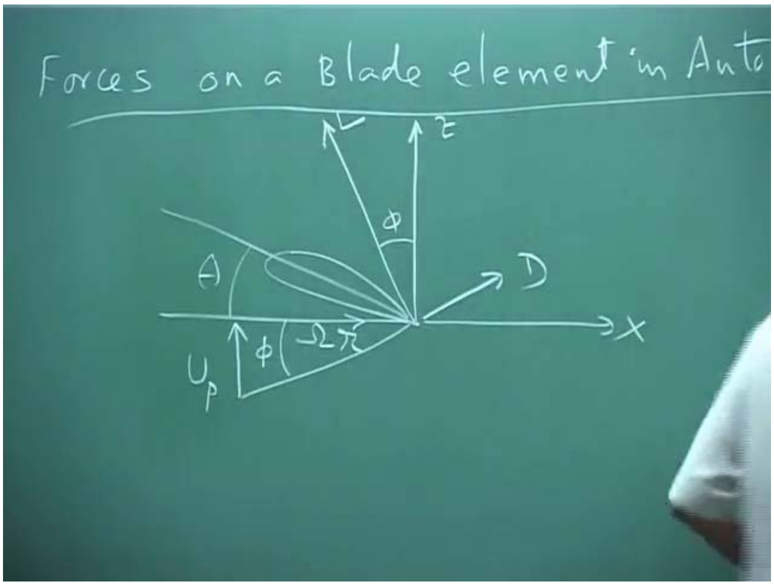

The power shaft, so note down this. Forces on, which I started, on a blade element in autorotation because here I am going to just briefly describe one section and then, we will analyze the autorotation condition and the physics associated with that. Later, you see the complexity, which actually happens in the real life.

You take an aerofoil, which is acting at the angle of attack, not Angle of attack, this is the pitch angle theta and this is omega r, which is due to the rotational velocity at that section and you have a, because this is descending you have a U p, this angle you call it phi and let us say, this is X because last time and the resultant and this angle is phi.

This is a very simplistic problem of an aerofoil, which has oncoming flow and flow, which is coming up because it is descending. U p includes descend velocity as well as induced velocity, please understand, that is why I use a very general perpendicular. The flow, that comes perpendicular to the aerofoil plane of rotation, that includes in the simple case the descend velocity and the induced velocity. Induced velocity is actually down descent velocity, is the relative (( )).

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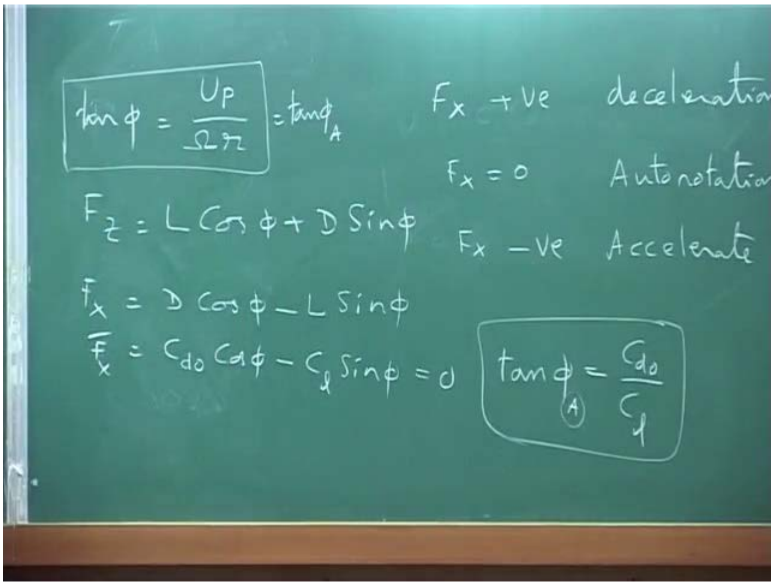

Now, tan phi, that is the induced angle, is basically U p over omega r. It is fixed, this angle is, once you know omega r, once you phi, sorry, U p, you know this angle, now if you calculate what are the forces that act on this element, that force is only the lift force, which you call it the force in the Z direction, another one is the X direction.

F Z is L cosine phi plus D sin phi and F X is, and I will say, D cosine phi minus L sin phi. Now, let us look at only the F X quantity. Of course, lift is dynamic pressure into, you say, it is the unit section. So, you take chord into lift coefficient, this will be a dynamic pressure chord drag coefficient. But this quantity can be positive or negative because the F X, F X can be positive or negative or it can be 0, depending on, of course, D and L contribute depending on the angle phi.

Let us define the angle phi, that is only the condition where this is 0 because if F X is 0, please understand, initially the rotor is rotating because the power is coming from the engine and that section is rotating with the omega r initially. Now, engine is shut off or engine is failed. So, engine is disconnected from the rotor and this is still rotating. Now, what will happen? You will have descend; you will generate an F X, if F X is positive. So, I will put F X positive, means, your rotor will start because no other force, only F X is acting. It will decelerate because F X positive deceleration of the section if F X is 0, that is, autorotation basically, because there is no force acting, it will continue to rotate with that omega r. So, it will, this is the condition for autorotation; that is why I said, blade element in autorotation will see what.

And then if F X is negative, negative means, if this is this side, then your aerofoil will accelerate. That means, deceleration means, omega r decreases here, omega r increases here, omega r constant, that is all, three. But this, we will relate to, from here in terms of coefficients rather than D and L because you can write this, as this will become F bar, you can take it C D naught because half rho V square chord is thrown out. So, C d naught cosine phi C l sine phi, you can keep this because C D naught is the aerofoil characteristic; C l is also aerofoil characteristic.

Now, you can take, if F bar X is 0 that is what is autorotation, I am going to call it tan phi, is what, C D. This is for autorotation condition, I am putting a subscript just to indicate, that this autorotation condition, tan phi C D naught over C l, it can, yeah, that we will write it later, that we will do it later, right now you take it as it is.

Now, you see, if this is greater than 0, that means what, you divide by tan phi is, what you do, if this quantity is greater than 0, this quantity is less than 0, correspond to this three conditions, right, yes or no? Because you say, let us write that.

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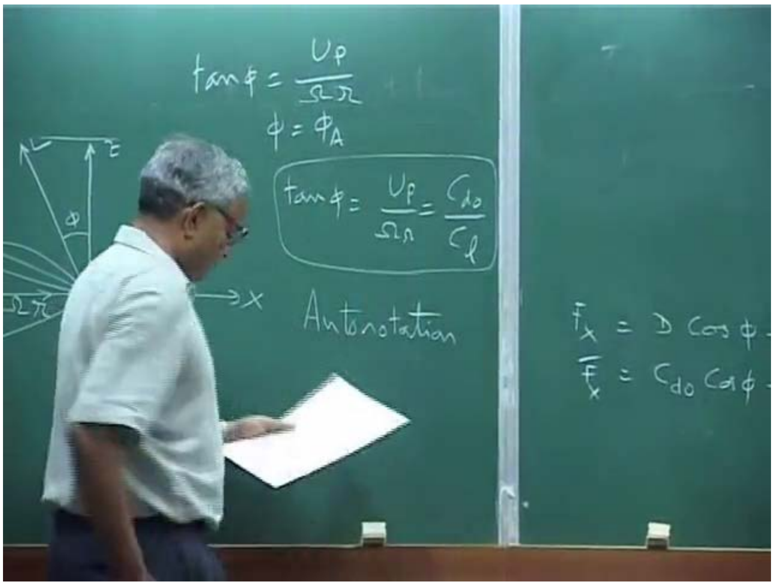

Now, you see, this is always valid, tan phi is U p over omega r. F X, then this quantity becomes equal to this value, which is, that is, phi equals phi a and then you can say, tan phi is U p over omega r, it is also equal to C D naught over C l. This is the autorotation condition; condition for autorotation for that element, is it clear.

I will always have some value for this. When this value is exactly equal to C D naught over C l, then I am in autorotation. Now, let us look at the other three conditions. This is deceleration. Well, I do not need this F Z, this also, this is also not necessary, I will write here tan phi is…

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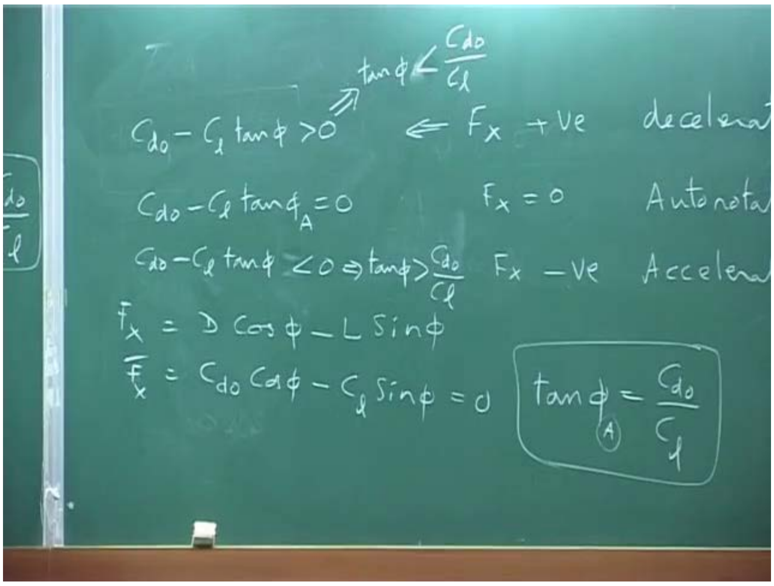

For this condition this is positive, means what? This implies C D naught minus C l tan phi is greater than 0 because C D naught, I am just dividing.

In other words, this is tan phi is less than this, is, is 0, this is the phi, I put it autorotation and this is the other condition, which is C D naught minus C l tan phi is greater than, sorry, this is less than 0. In other words, this implies tan phi greater than C D naught over C l. Now, you have three.

What we will do is, we will go ahead and you take an aerofoil, you know, it is a characteristic with angle of attack. Now, what is my angle of attack?

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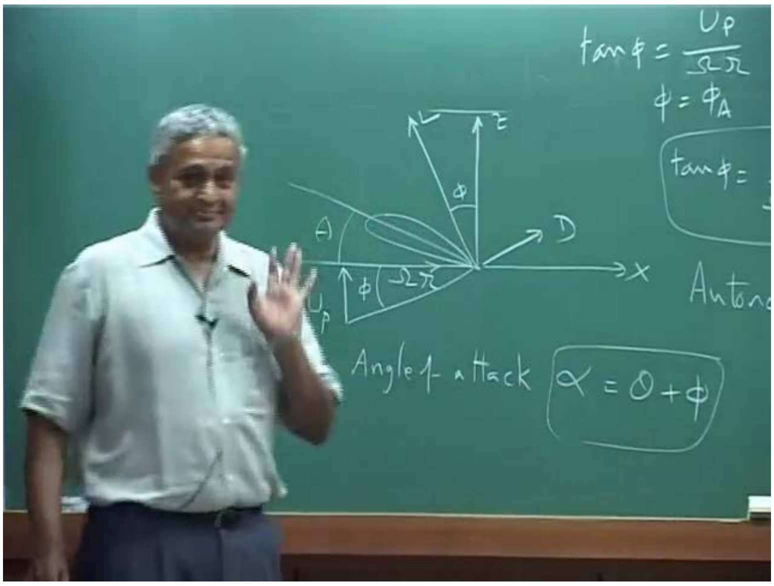

Please understand, my angle of attack is basically alpha, I call that, which is, this is my angle of attack. Now, I take an aerofoil, any airfoil, draw the curve. I maybe, I erase this part because this is right now not required.

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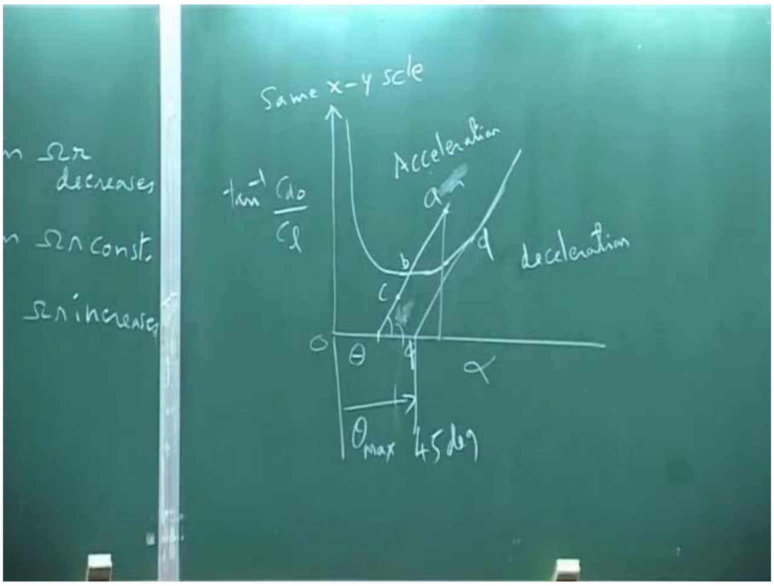

We will plot the curve of tan inverse versus alpha, but keep the axis same; axis in the sense, x-y same scale I will put it. So, you plot a same x and y scale because both are angles, this will be like this, maybe I am not drawing properly, it may go something like this.

This is the curve for a given aerofoil, you, you follow what I am saying because you take any airfoil, you know the drag value, change the angle of attack and then plot tan inverse C D naught over C l like this.

Now, this is very interesting, this curve is very, very important for, now what is my angle of attack? Angle of attack is theta plus phi, now I, this is 0, I take some theta, this I call it theta. I draw a 45 degree line from here, this is 45 degrees. Now, this is same scale, if I take any point here I think, that point I have noted at a, this is b, maybe I will put it, this is 45 degrees and some point C.

If I take this, this is phi because I am taking actually 45, does not look like 45 because this is phi and this is also phi, you follow. Now, if my this phi is greater than this curve because point a, phi is greater than tan inverse C D naught over C l. That means phi is greater than C D naught over C l, follow, which implies what? It will accelerate. When it accelerates what happens? Omega is increasing, when it increases what will happen? phi will decrease, so it will come to that point b, you understand, because at b exactly, phi is tan inverse, that is the autorotation point.

Now, suppose your point is below, that means, phi is less than tan inverse C D naught, phi is less than this, that means, it will decelerate. So, it decelerates means, what happens? Omega r is already large, so it will start decreasing; when it decreases, phi will increase. So, it will go to b, that means, in autorotation it is a stable point, but what is the pitch angle you can have maximum?

Please understand, suppose I go and I draw a tangent to this line 45 degree, this point, this is the point D, this is theta max, any point here, this is acceleration, this is deceleration. That means, I take theta m, draw the 45 degree exactly, it meets this curve at a tangent, that means, this is the point. I can have any disturbance, if I go beyond, my rotor will start decelerating, that is all, it cannot take it, you understand. That means, theta m is the maximum pitch angle you can have. Otherwise, if you go to a pitch angle, which is beyond this, every point is deceleration. So, the rotor will simply decelerate from omega r, it will stop and it will start rotating in opposite direction, that is very dangerous.

Now, it is not that you can keep initially when you are hovering because with the power pilot will be operating is collective pitch or whatever pitch angle at some value. Now, it may be more than this, you can be more than this, there is nothing because it is the flight condition, the weight, everything matters. He may be operating at a pitch angle, which is larger than this, usually that is what happens.

The moment engine fails, the pilot is told, they use the word dump the collective, that means, reduce the collective angle, that means, decrease immediately, otherwise if you hold it, there rotor will stop and immediately, he has to reduce the collective. But how much he will reduce, that is another question, usually reduces?

Now, the interesting part, there is again one more interesting thing, you know, that tan phi is U p over omega r. So, what is the maximum omega r you can have?

When you have maximum omega r, phi must be minimum, minimum means, the minimum point on this curve is the point where you will have maximum omega r. So, that is why, if you decrease your collective from this point or anywhere, what will happen? Omega r will increase, but if you decrease further again, that will start decreasing. So, you will have a maximum omega r in the rotational velocity, will happen only at the point where you have this is minimum.

Now, these are all drawn for an aerofoil because you can draw the, because this is purely aerofoil characteristic, which is done in the wind tunnel. You will find, that normally most of the industries, of course, there are several reasons. Autorotation condition is one choice of aerofoil and then they will also have, know, knows down pitching movement, there are several reasons.

So, you will find, that industry develops their own cross-section of the aerofoil for rotor blade and then, they use it, it has evolved over years of their testing. So, they would not, you know, reveal all the details. Now, this is very interesting physics.

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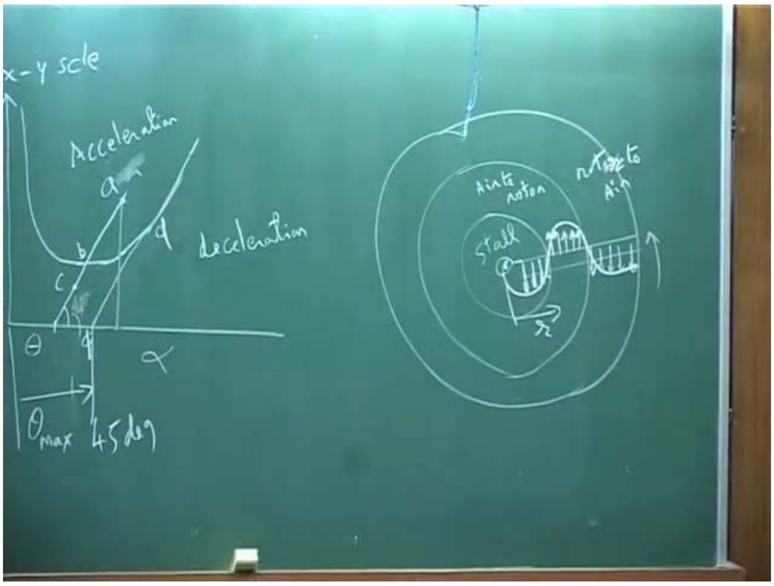

Now, if you translate it to, what we did for one section, you translate your actual rotor. The actual rotor will be like this because I am and this is the direction of rotation. So, you have the blade, it is like this, this is, now you see, phi is large because omega r is small near the route. That means phi is large.

Blade may stall, that is why we drew the diagram here, Stall. Then, you have another region where phi s becomes smaller, because from large I am decreasing. Now, here in that zone, I may have, this is where power from air to rotor, it is air to rotor, here it is actually rotor to the air, that s, it is like a normal operation. This is from rotor to, sorry, rotor to air.

Now, drag force will be here, acting here. Also, drag force will be there, I do not, I am not showing it. Now, you see, this is stall, this is pulling it because phi, you, you will always accelerate. phi X is still because initially, this angle is large, you are decreasing it. phi X is attached, flow phi X is actually accelerating, this may be somewhere, at one point it may be 0, F X may be 0, then if you keep on decreasing phi because what, decreasing phi means what? Omega r is increasing, as you go towards the tip omega r is increasing.

Then omega r increases phi becomes small, when phi can be small, you are actually decelerating, that means, r is actually dragging the rotor. So, this is, this is how the loading will be. So, it will be drawn something like this, something.

You see, the integrated value of this, this is a very, very interesting problem for autorotation, what we should not have any problem. And integral of this drag force, one is integral to drag force is total force, but integral of the r into the drag force, that is the moment, that is, this is you take it as r.

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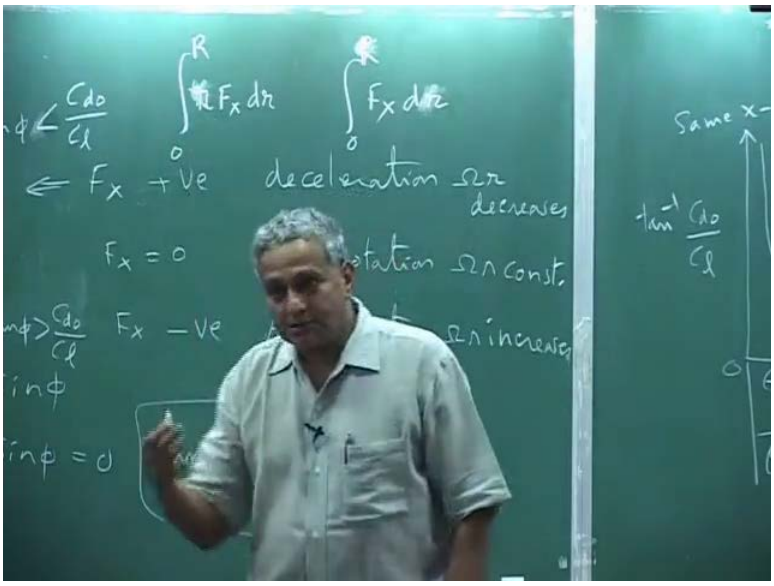

Integral F X d X, that is 0 to 1, you take it and this is the total drag force. Another one is integral 0 to may be r, capital R, I am sorry; maybe I should use d r, r F X d r. This is the torque, now what, what should be the condition for autorotation? You have drag force; you have torque, then what about force? It is a very tricky stuff, technically both must be 0 because drag force must be 0, torque must be 0.

Now, how do you achieve that, that too with that kind of a distribution? You have a distributed force, now they have to get it that is why, it is, it is a tricky problem if you really want to solve it. How my forces will vary? Because you have to do it, make sure, that, that is 0, maybe you, it should be possible, it is possible to satisfy, but whether that force is like, because the force is aerodynamic drag, it is not, that you are applying the force. If you can apply the force, that is ok, but this is an aerodynamic force. You may find one of them is 0, another one maybe a little bit there. Because I have not done the calculation, but I thought that this is a very, very interesting problem in the real life situation if you want to do.

But usually, they will say torque is 0, good enough or you say drag force is 0, that is also torque is 0, because you are everything relating power. So, I will say directly, torque is 0. So, I do not bother about, but dynamically if you want to look at it as a full problem, it is a rotor blade, there should be no force on that. That means, F X must be 0 integral, the moment also be 0, satisfying both is very, very in real life situation, but you will find, may be a little F X may be there. I am not sure what really happens in the actual rotor system.

Usually, this is the (( )) because I thought that it is quite interesting from Physics point of view and steady, please understand all assumptions. Now, you will say, you may ask lot of questions, how do I know what is my U p because U p consists of descend velocity at an inflow. I do not have clear definition for inflow in the turbulent wake state; I have in the other state, windmill break state, but not in the turbulent wake state. So, these are problems.

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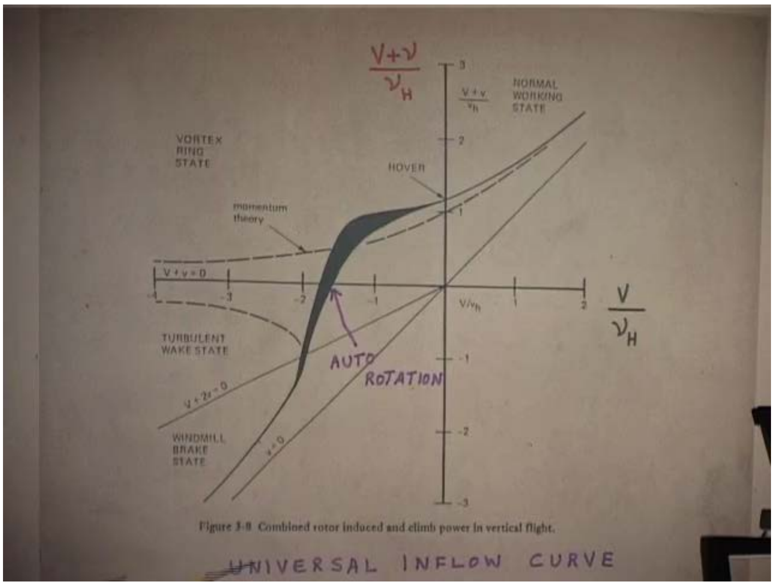

Now, you slowly understand, that even a simple descent thing is not very easy problem to analyze because the, because we showed, that one minute, I will show this diagram also, this is just a dark patch. So, you have to make an approximation to the climb and I say that is my inflow that inflow may not be exactly at every point. You do not know what, but you have to make an assumption, that my inflow is constant over the whole rotor disk, which is not true.

Now, you see, the amount of assumptions you make, which are really not correct, but still you have to get an answer because you cannot. So, usually the power is 0, they take it and use that condition, come to autorotation, that is all. It is a very, very, from mathematical point of view, it is a complex problem, but what is normally done, it, take it as the simply curve, show that C D naught by L, ok minimum, this operates, fine and I will have my rotor loads and you take typical one section and then say, if that section is somewhere around, I do not know what, because the whole thing goes in a particular fashion.

That is why this is shown to the pilot usually because this is aerofoil characteristic C D naught, because you are not doing anything autorotation, you are just plotting that and minimum point, you say, ok, hey the pilot should come immediately, dump the collective below. But then, autorotation is a stable rotor, will continue to rotate, but what rpm it will achieve? That rpm depends on what C value you are operating on, is it clear. I think with this I close your, all what you have learnt in climb; climb is a very, very smooth thing, whereas descent is most complicated problem. Even today, if you go to industry, they will have some thumb rules; just follow that; that is all.

And autorotation, another important aspect is the inertia of the rotor because the rotor should have sufficient inertia. Inertia means mass into r square because it should be, because if it has a large inertia, it will not decay faster because pilot takes some time to react. You are operating at a higher pitch angle and engine fails, immediately drag force will try to stop. So, how do you take the inertia? What inertia you should take, so that the rotor should have that sufficient inertia? Because if it is very large, then it is aircraft is going to be very heavy, the blade is going to be very heavy. But if it is very light, blade will stop. So, you should have sufficient inertia and there are some guidelines at least, that much you should have that inertia of the rotor. So, that is another aspect, this is purely from aerodynamics. We are not looking at the inertia aspect because this is a very complex problem simply because you do not know what the inflow is, that is all.

Dynamics you can fairly clear, yeah…

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What reaction?

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Net force, no this is, we have plotted this for a section…

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Which one, this one? This is net force, yeah…

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That force is acting on the system on the helicopter. See, if I isolate the blade because every, see dynamically you have to look at it. I can have 0 reaction force, what is the problem?

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See, what you are saying is, you are holding it, just because you are holding it so there is a force you are saying.

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No, but then, but there is a force acting…

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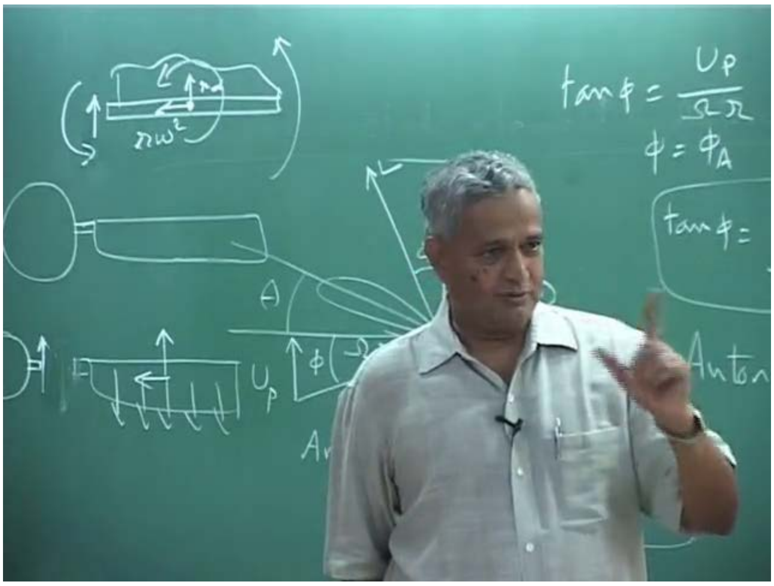

Wait, this is a very tricky thing. You take this, this is the blade; you say, if I isolate this, isolate, you say there is a force acting somewhere, I do not know whether this way or this way. If force acts what will happen to this body from basic dynamics?

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This is net; if I isolate a body you say there is a reactor. Yes, I agree, if you have a force, see this is the other body, right, this will be like this.

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Which reaction?

That the net aerodynamic force can, you said, that it cancels, cancel means what? This is, it should be 0. See, you take the aerodynamic force, this is a rigid body, you are having aerodynamic force acting on that, so the forces act on this are, I am just drawing. This will be resisted by this you may say, maybe other way round, whatever you may put it, but then, this entire force has to be what? At the root you are going to have a moment, see total force that acts on a body, it has to be 0 and you say moment is 0.

There are two conditions. I have isolated this body; this body is initially, though it is rotating with a steady omega, that means, you will have only acceleration towards the center, there is no acceleration in the tangential direction. But if I isolate the body, if I have a resultant force, that means what? It has to have an acceleration or deceleration depending on whatever direction you are having. Now, deceleration will stop, acceleration may take it up, I may have torque 0, you understand. Then, it is like a rigid body, I do not have any moment, but I have a resultant force; can you have like that, yes or no? See, what I am saying is, if you neglect, if you have a leftover force, that force will be resisted by the reaction here, you understand.

See, basic mechanics of solids, what you do, you take a beam, you apply some load. If you apply just this load, will it be stable? No, because you have to have a reaction at the root end, the reaction depends on what you apply here, agreed or not? Because you should have a reaction force, you will have some moment or whatever it may be, you will have something. This is depended on this, this is purely static condition, agree?

Now, this is the net body force, but I want the moment 0 because the torque, the rotor drag is going to come, it will try to stop the rotor, I do not want the rotor to stop, that means, what? That means, what this must be (( )); hey, balance means what? This is balanced, always this is balanced in static condition, I want torque to be 0, but when I make torque 0, am I making the force also 0? Not necessarily, that is what I put, this is, torque is 0, this is the force, it, it can be, need not be, I do not know, you follow. Now, if you take it as a problem, that I need to get both of them 0, you know just a mathematical problem.

There can be a slight thing because autorotation, they do not keep on going all over the place as usually, it dumps the collective rotor, rpm will come to some stabilized value because now, you see the minimum phi, which we said is maximum omega. Whether your maximum omega is what you have designed, because please understand, you rotate the rotor at a particular omega because that is a fixed omega, are you going to achieve that omega or you are going to some other omega, which is higher than the design value or is going to be less than the design value? So, these are other issues. If your omega increases more than your centrifugal load, everything because the root will get tremendously structurally strained.

Static equilibrium is, once static equilibrium, this is 0 you say, understood, but our situation is this and you have a dynamics also it is there.

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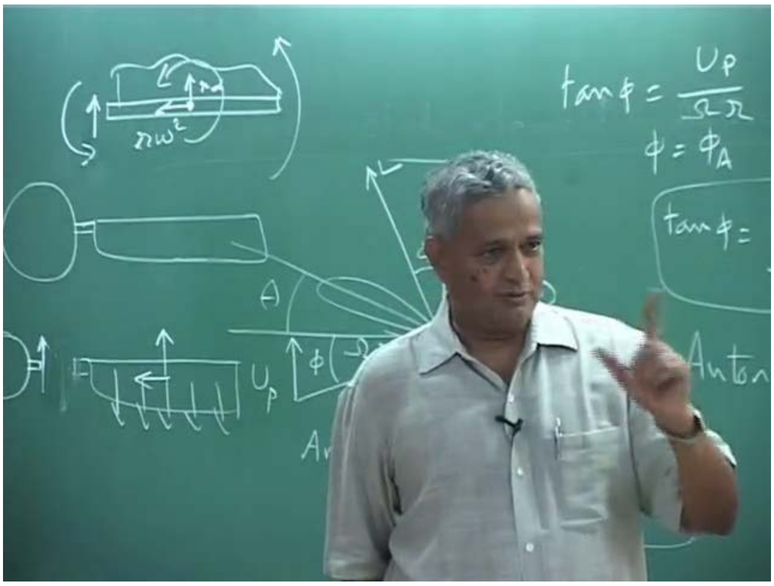

So, you will have your dynamics is what? The mass, you may, suppose this is, this is, that is why it is little bit complex. Problem there is a mass center; mass center will have acceleration, agreed. So, it will have, because this is rotating, it will have acceleration towards the center, it can have a tangential acceleration, agreed. That is the mass center, and then, this body is also, there can be an angular acceleration, agreed.

Your angular acceleration must be 0, then torque is 0, but your tangential acceleration, is it 0? Because you want it rotate at constant omega, constant omega if it rotates means, this must be 0, because there is no tangential acceleration of the center of mass. Because this is basic dynamic you know, that this is, this is r, this is r alpha, you know that from basic dynamics, rigid body dynamics. Tangential acceleration r is fixed, constant r and that is alpha, now this should be 0. So, you need to have, every condition should be whether you will satisfy, usually torque is set 0, that means, your rpm is take it.

But I do not know, whether the forces are really balanced to 0, but it may come very close to 0. See, there will be some redistribution of the loads because you need to maintain because you do not want the rotor to, that is why pilot dump the, may not hold it at the same value, he may keep changing a little bit, that only you have to ask the pilot. But as Physics of the problem for a 2- D aerofoil it is explained, but then real situation is much more complex because you will find different sections of the rotor blade operate in different, different conditions. Some will be accelerating, some will be decelerating, the condition of these effects, is it clear. So, I have confused you enough. So, autorotation is otherwise simple; if you do not want to get into this business, autorotation is, power is 0, that what, what and that is good enough, yeah…

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No, no, this is alpha, this, this is X-axis is, yeah, yeah…

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Yeah, yeah, all these points are stable, will be stable here, every point is stable.

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Yeah, yeah, see this is done for a section, you understand. But that is why I said, section means, which section you are exactly balancing this. That means, somewhere F X must be 0, they may be here and here I do not know where they are, but other places you are having the force in those places, you are actually operating faster.

See, this is for a section, this is for the rotor, every section cannot operate here, it is not possible to operate, you understand. This is shown only two-dimensional aerofoil characteristic; that is all, is it clear, am I… You integrate over the blade…

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Yeah, yeah, see some point you may be here, some point you may be below. So, some points you are accelerating, some points you are decelerating, integrate, that is what? Some points you are accelerating, you are decelerating, net is, net is 0, that is why you have to integrate the along the blade knowing the characteristic. Otherwise, mostly in the industry, they may take in my opinion a typical section.

Typical section in a helicopter is about 70 percent or 75 percent, but that is, I do not know for the autorotation, whether they take that value, it could be even 60, I do not know, but you may be able to tell me. For that section you satisfy this, after that rest of, then take over. But here you see, please understand, you have not considered the elastic twist of the blade, nothing is considered. This is like a rigid blade because I keep a pitch angle and then only the inflow angle is taken, you follow.

But in real life it is not just the inflow alone, you are going to have even elastic twist of the blade and then you will also have blade flapping, please understand. So, that will also give velocity. So, it is a, it is a more complex thing, that is why, what industry will do? Autorotation is, you have the code, you say power 0, the condition for, which you keep on solving the problem for different descent velocities, you solve the problem, the trim of the helicopter, you solve the entire problem assuming some inflow velocity because that you have to take this curve approximation. You say, if I design at this velocity, this is my inflow, calculate every section, what is the drag force, integrate over the whole thing, you will know what is the power.

So, they will keep on drawing the power curve with respect to climb and descent, wherever it meets 0 or you extrapolate to 0, that is the descent velocity that is all, they go for power evaluation not by section. But for explanation from Physics point of view, this is done because it depends on the aerofoil characteristic, but he is told reduce. That is why, why pilot is, whenever they say you decrease the collective, do not, see, there is very, very, see the general tendency is, if you want to go up what you do?

You increase the collective, but provided the rotor is attached flow, you increase the collective lift, will go up. Sometimes if your angle is already large, you increase (( )), you may be going down further. Then, in that case it defines your logic, hey I have to reduce the collective, so that get it attached flow after that climb. But usually, the instinct says, hey if I reduce the collective, I am going to go further down because in autorotation what is going to happen is going to come down, the helicopter is going to come down, engine fails because there is no power, it is going to come down.

At that time what we have to do? We have to decrease it, you follow, and you decrease it to, because if you are here, that is all, your rotor will stop and it will start rotating backwards. So, you decrease it such that you are in a stable zone, that is why he is told decrease, but how much he should decrease, that may be way to do vehicle or something. But this is drawn for aerofoil, not for the integrated value of the rotor because integrated if you have to draw, that is difficult task; yeah…

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No, no lag hinge may be there. See, lag hinge, yes, there is, because please understand, moment you have to come, a force will come.

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See, lag-hinge is not right at the center of the shaft, you understand. How rotor is rotated? How power is given to that, how do you give? Because if you have a hinge, suppose you say, this is a hinge, by rotating this will you rotate this, how no hinge? See, this is the shaft, I put a hinge, if I rotate this what nothing will happen? So, I cannot have centrally lag-hinged rotor, I, yeah…

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From the hinge it will go. How it will go is, this is what, you take this, this is the or in this diagram, let us take, this is the…

You have a hinge in this direction and you may have your blade starting here. Here is the hinge, this is free to move back and forth about this point, but then a force will come here and that force gets transferred as a force and moment and that is how you will be able to rotate the helicopter, otherwise if I directly put the hinge right here, if I rotate the shaft, blade will not rotate. So, you do not have that situation always. You will find, that transfer of power is there by the offset, but this offset is (( )) most of the rotor they will have.

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That is all transfers to the hinge; it will go, transfer, it will get transferred. Because otherwise, without, see hinge is, is a good design because you do not transfer the moment, but if you do not transfer anything at all, then how will you rotate in the first place because if I put a ball bearing, attach the rotor and in the inner rays I attach the shaft. What will you do if you rotate the shaft? Blade will just stay as it is, it will not, blade will not rotate, follow. You have to have an offset and of course, the offset come because of physical constrain also. So, you need to transfer the rotation, is this clear or to an extent?

Because this looks a little interesting, I thought I will give the physics because there are people from industries. So, it will be interesting to know how things are really happening in actual, it is a more complex problem. Now, let us, this is just a brief thing, what you call the ground effect because this is just for information to you because there is no calculation or anything like that.

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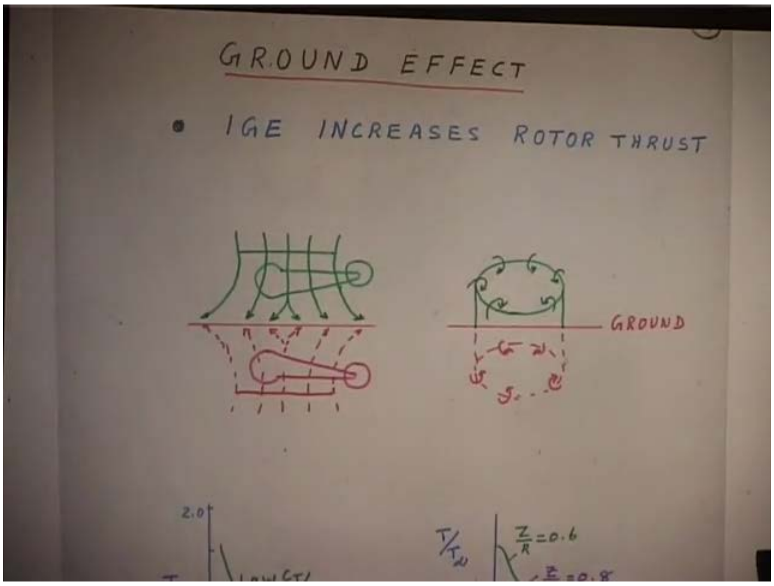

This is the ground effect; what ground effect means? Your rotor is operating close to the ground rather than far away. Because if you look at it just from what happens, the rotor inflow comes, it hits the grounder, that means, the normal velocity should go to 0 at the ground level.

Now, this particular thing is idealized very simplistically. Your rotor inflow, you put a mirror image here because this is a method of mirror image. You put another, as though fictitious rotor is rotating beneath the ground, such that both of them are giving an inflow. This inflow will come up like this, that inflow goes down, both cancel out and leaving earth as the, ground as 0.

Now, the effect of this will be to reduce the inflow there because you are pushing the (( )). So, what happens is, to lift the same weight the power required to hover near the ground is less. Because you have induced basically power, induced power, your induced velocity you require less, therefore the power is less. So, if you are hovering near the ground, you have, you require less power, but in other words the same thing is plotted in terms of thrust. You, if you give the same power, that means, you can lift the more weight near the ground.

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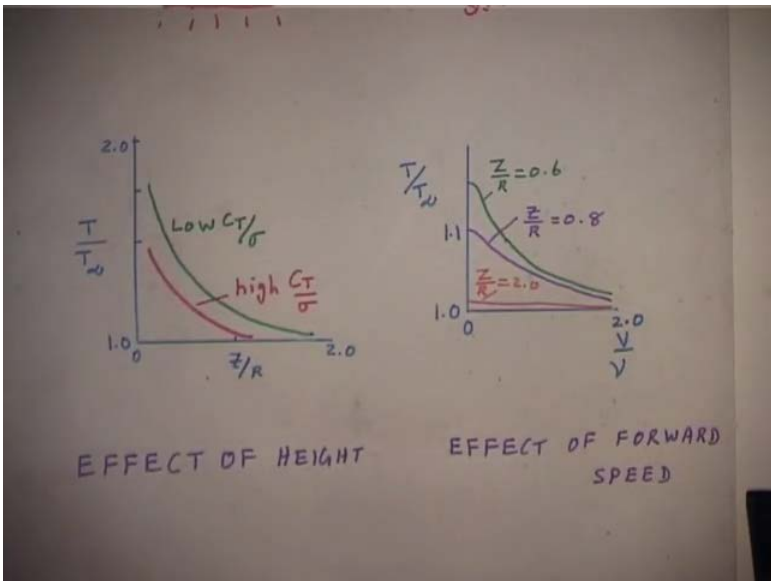

So, that is why, that particular thing is shown as a diagram, that is, T over T infinity, T is the thrust. Rotor thrust over T infinity is when it is far away from the ground and the curve actually starts from 1 to 2. Here, Z over R is the height of the rotor with respect to the ground.

Now, you see, as you come near, take this curve, that green, as you come near to the ground. Your lifting capability increases for the same power because this is drawn for same power. So, you see, I can lift more weight if I am near the ground. So, this particular thing is used because if you want to carry a little they also go a little forward, so that the power required becomes less. So, you carry a little extra load and then you can take off and fly, but of course, this effect is highly dependent on forward speed, which I meant is cross wind. Suppose, you are hovering near the ground, suppose there is a cross wind, what will happen? The wake will, instead of coming down like this, if we swift, then suddenly rotor will lose thrust, that is why, this is also dependent on the forward velocity, the effect of ground.

Depends on if the forward velocity is to induced velocity, if it is more than 2, you see, is has no effect T by T infinity it has. The whole wake is pushed backwards and the effect of ground is lost. It is quite sensitive to side winds. Usually, the thumb rule is, if you go beyond 1 rotor diameter, ground effect is, you can take it as 0, there is no ground effect; 1 rotor diameter, that is the general thumb rule. And there are some expressions given some earlier because we are not going to use this. Basically, this is for information because if it is near the ground, you can develop more thrust that is all, for the same power because this is called the ground effect of the helicopter rotor. From now on, it is forward flight. The entire course will go because this is much more complex problem, because I have indicated the complexity in hover.

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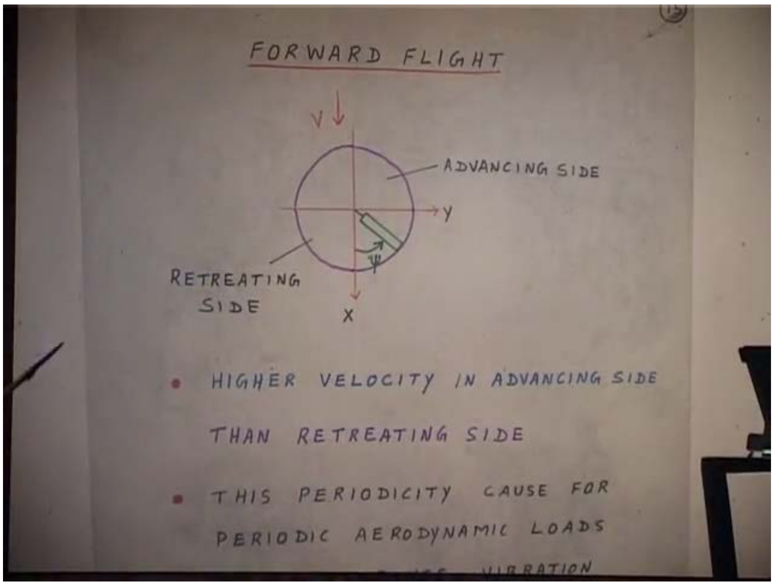

Then, of course, climb in forward flight, why it is complex? Because we split the entire rotor disk, assume, because later, we will define all the velocity components motion, etcetera, everything will be defined. You say, this is a rotor disk you are viewing from the top. Now, here in this course, I normally take counterclockwise rotation is positive and my rotor is rotating in the counterclockwise direction, but usually you may ask, which direction the rotor rotates? Europeans rotate clockwise, Americans rotate counter clockwise, why it is anybody's guess, it does not matter as far as the rotor. Only thing is, pilot has to get adjusted to that little bit the direction of rotation, otherwise all the calculations everything is same. Somehow American helicopters, they always rotate counterclockwise, whereas all these European, the Germans, everybody, they, they rotate clockwise.

So, we are going to take the counterclockwise rotation positive. So, that is why, I put psi and psi is basically the azimuth location, which is omega T and omega is the rotor angular velocity. And if you take kth blade, it will become psi k. Now, you see this rotor, in the earlier case it was just stationary, now it is moving forward.

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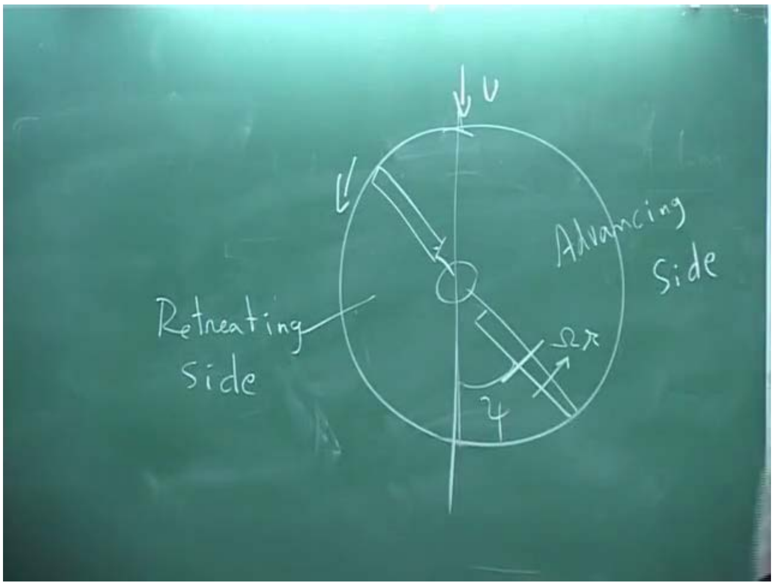

So, the forward direction I put it up. So, there is a relative wind V, which is coming towards the rotor. Now, this is also rotating, this is having omega r, so you will find... So, this is, you will have this is omega r and you have V and this is psi, that means, in this half, the relative air actually acts. That means, the rotor section experiences a larger velocity of wind, whereas in this half, this is actually moving this way; that wind is also coming, so there is a reduction in the velocity. So, this is advancing side, this is retreating side, this is briefly (( ))

Now, you immediately know because my velocity is now varying, oncoming flow is time varying because if you take a cross-section or basic aerodynamics says, what is the normal velocity, but that normal velocity is no longer a constant, it is varying with time. So, now, you know.

In your aerodynamics we have a situation where my oncoming velocity is time varying. This is the first complexity between fixed wing and rotor wing because you do not do. In fixed wing theory the time varying, oncoming flow, it is all fixed.

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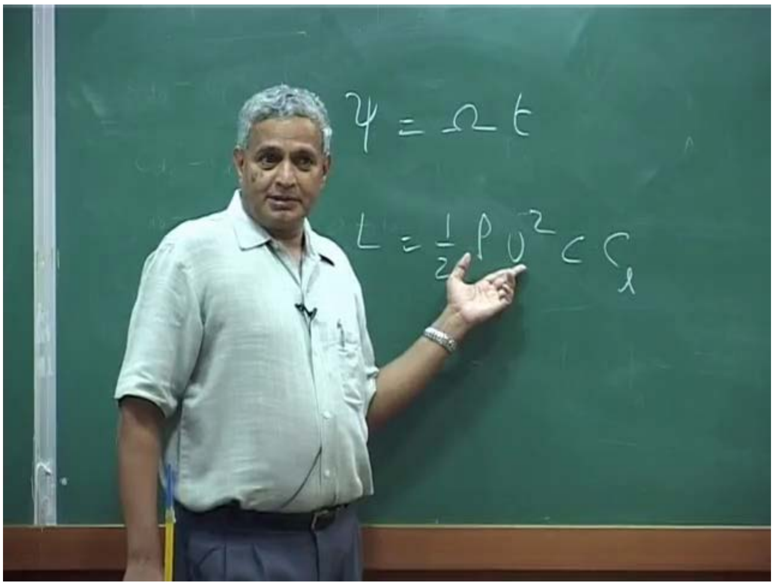

Now, what happens because of that? Because of that if you use directly the formula, lift is what? Half rho dynamic pressure chord C l lift per unit length, this is varying, time varying and square, that means, if it is 1 harmonic, it will go to 2 harmonic also. So, your loads are now having time varying, they vary with time. The moment you have any load lift is a lift holds acting if aircraft is steady flight, please understand. This is a steady velocity, V is steady, omega is steady. Even if both of them are steady, I am having my lift force as a result all the aerodynamic forces changing with time. When they change with time, because this is like a beam, I am having a load, which is changing, that means what? That blade is going to respond because it is a flexible blade, it will respond. Now, when the blade responds, so you see higher velocity in advancing side, then retreating side. Now, this is the first complexity.

Now, blade responds this periodicity because you are varying cause. This is the root cause for periodic aerodynamic loads, please understand. Periodic, I did not say harmonic. It is periodic because you will have, all harmonics will come because you, you will be, you will see later, is a highly complex.

You, even if you take first harmonic because this is 1 per revolution you are putting square. When you put a square, if a sine psi is there it is going to become sine square psi; sine square psi you can put it in cosine to psi form. That means, you are getting second harmonic. Now, you will find, slowly you will keep on adding all the harmonics, harmonics means time varying.

The moment you have time varying, what you are going to have? The blade is going to respond; blade is going to vibrate. Now, blade response you cannot neglect it in forward flight. You cannot say, my rotor is rigid, it does not, no matter I may oscillate my load, but my blade is not going to respond at all, that is why, that is our assumption you can make. But then, you cannot fly because then it is like a propeller and the propeller is very stiff, whereas in helicopter, the blades are not stiff, they are very, very flexible. So, response of the blade you have to include, this is what the aero-elasticity. Now, you see, aero-elasticity cannot be separated from helicopter dynamics in forward flight I need.

In hover, you please understand, we never talked about blade motion, only blade pitch angle, inflow, nothing else. We did not even mention about flap, lag or torsional deformation, nothing. We treated as though blade is rigid, we did not even mention about its flexibility, whereas in forward flight, you cannot do that, you have to have the blade response.

Now, when the blade starts moving up and down, now this is adding another complexity. My load is changing; as a result, my blade is oscillating. Now, my blade is oscillating, therefore what will happen? My load, also because my angle of attack, everything will change, as a result, it is an aero-elastic problem. You cannot split these two because what we normally study in aerodynamics? There is a steady flow, the angle of the aerofoil is captured, some pitch angle you find, the lift you find, the drag wonderful and you find the pitching moment; this is a steady case.

Now, here, one is, the V is changing; because of the V, this load is changing; because of the load change, this is going to oscillate up and down; now, when this oscillates up and down, that is going to change the angle of attack, everything. So, my load is, this is the simple aero-elastic problem, but it is complicated.

Now, how do I solve? I do not have any theory, which says, that this is an unsteady aerodynamic situation, but I still use whatever you have learnt in basic aerodynamics steady flow. We will use the same condition and that is what is, of course it is complicated, in research level you complicate the whole thing, but here for the course, you know, we will do it very, very simplistic.

And then of course, you see, because vibration, because we have this is oscillating, so you have vibration. You also have these two phenomena, which is stall, the blade will stall. Why the blade should stall you may ask? The stalling is your angle of attack, is going up beyond the, whatever the stall angle here, advancing side your velocity is more, that means what? You will generate more lift, please understand.

Retreating side, velocity is less. If you keep the pitch angle same, then one side you generate more lift, other side you generate less lift assuming inflow is same; inflow is another problem. Then, what will happen? The helicopter will roll. So, what is done is, pitch angle at the advancing side you reduce it, on the retreating side you increase the pitch angle such that you balance both and this is done through the cyclic control, which you had. Now, when you increase the pitch angle you may also stall somewhere that happens at some forward speed. So, you will have dynamic stall as part of aero-elastic problem.

Then, the other one I mentioned, reverse flow. You know, that this flow is coming, this is omega r. If this is small, omega r is small near the root, the flow will be coming from trailing edge to the leading edge, this is called the reverse flow. So, you have all problems related to aerodynamics in the forward flight.