Introduction to Helicopter Aerodynamics and Dynamics

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Lecture No. # 08

We derived the climb and descent.

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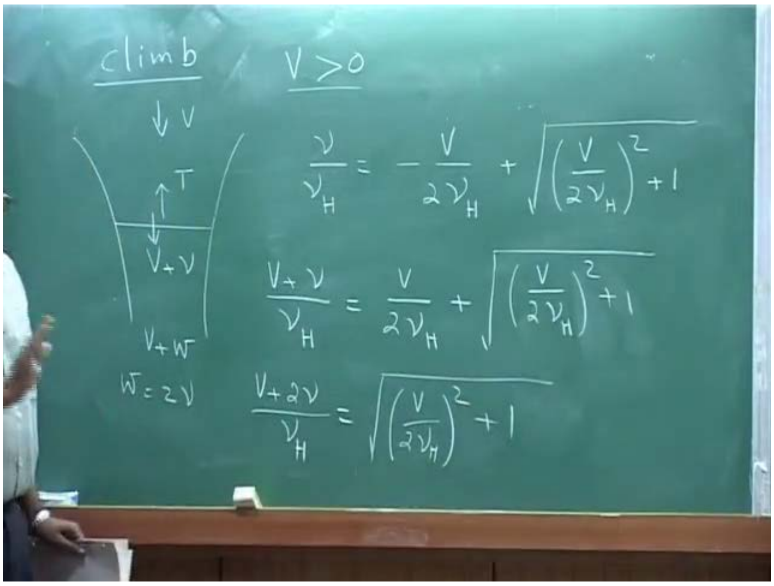

We had the climb condition and we derived the expression; that is, V is positive in this. And, we got the expression for induced flow as minus V over 2 nu H plus root of V over 2 nu H whole square plus 1. And then, nu H is hover inflow. And, we also wrote V plus nu over nu H – this is the velocity at the rotor disk. This is V over 2 nu H plus root of V over 2 nu H whole square plus 1. And then, the farfield – we wrote this V plus 2 nu over nu H equals root of V over 2 nu H whole square plus 1. These are the expressions we got for the climb. Similarly, we derived for descent using the different set of condition.

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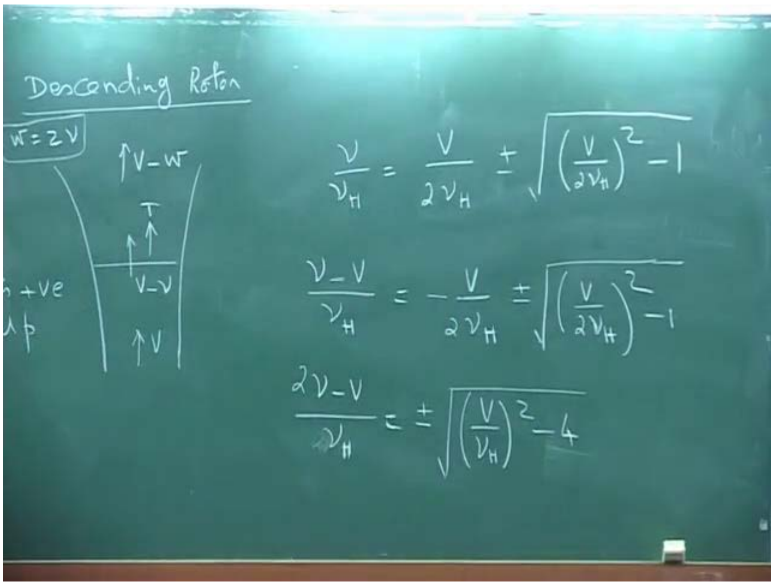

In the sense, I will write here Descending Rotor. Here our diagram was slightly different. We used the direction of velocity; we put it up; and, here we said V minus nu; and, we made it V minus w. Again, w is 2 nu; even in this case. So, you know… And, thrust is this way; nu is down. But, in this case, V is positive up; whereas, here V is positive down. And, we got the expression. Now, I am going to combine and then put it as one big expression, which is much easier. We got the inflow (Refer Slide Time: 04:17) nu over nu H equals V over 2 nu H plus or minus root of V over 2 nu H whole square minus 1. And, at the rotor disk, it is the other way I am writing it; we wrote it as minus V over 2 nu H minus plus root of V over 2 nu H whole square minus 1. And then, 2 nu minus over nu H – this is minus plus root of V over nu H whole square minus 4. Is it correct? Or, you can put it as expression; kindly check it. Here this I should change it to – (Refer Slide Time: 05:41) this is plus; because I am multiplying by 2; 2 2 will go up. You now have one set of expressions for descent; one set of expression for climb. You can plot both of them in one diagram.

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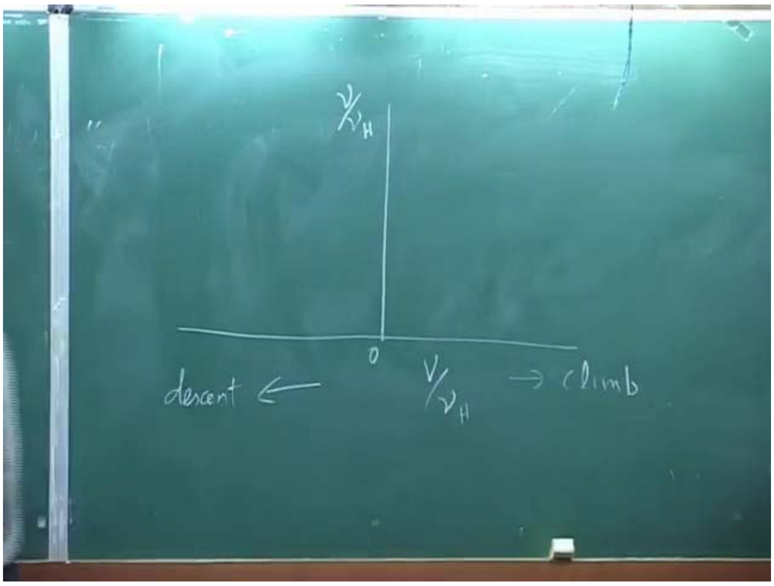

That means, I am going to specify… If I want to plot X-axis – I say V over nu H. This is basically climb. This is essentially descent, which is a negative value. And, the Y-axis – nu over nu H. Now, you can take it this expression and directly plot it, but you have to be very careful, because for the descending rotor, we took V up – positive. So, that means, here I may mark negative, but actually, I should use plus only. On the other hand if I want to call the velocity – if the helicopter is going up is positive; coming down is negative; then, in these expressions, I can just change the sign (Refer Slide Time: 07:34) – sign of purely the velocity. If I change the sign, then you will get that. When I use descent, I have to put minus V; not plus V as is marked here. So, if I change the sign… I have to erase this, because this diagram is not directly… because I have used this symbol, because this much easier for understanding and getting that expression. But, in some other books, they give the opposite. In the sense, the sign is already taken into consideration in writing this expression. So, if you do that, that expression will become… So, I erase this; V is negative downwards. So, here you see…(Refer Slide Time: 08:32). So, I am going to simple erase this diagram and then I will write descending rotor.

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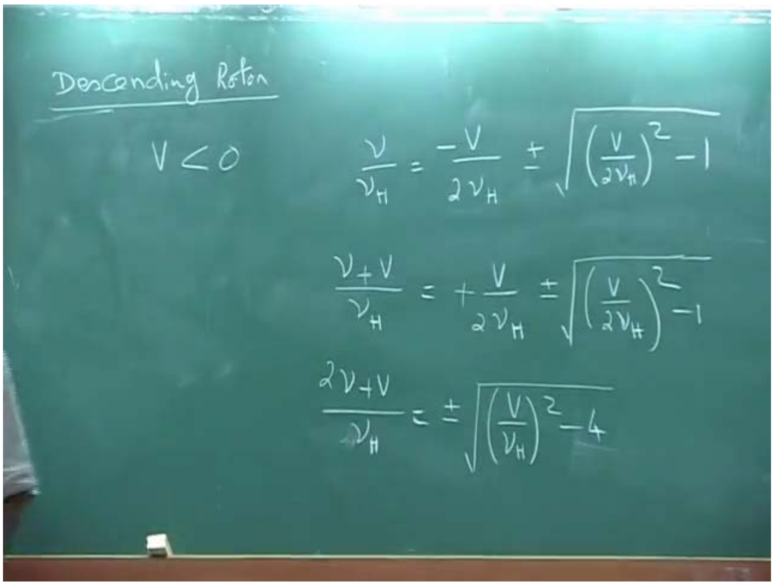

There V positive; here I will say V less than 0. I will put a minus sign here and this will become plus; plus; plus; that is all; just the sign we change; whereas, inside the square, anyway, because these are all square terms. So, it does not matter. So, only change of sign. Now, what happens is I can directly go ahead. If I want descent, I will simple put V is minus V; substitute here and get that. Actually, if you put minus V, this will become plus. That is what we had earlier. So, everything will be fine.

Now, we will plot this curve (Refer Slide Time: 09:30) assuming that these are valid everywhere. Suppose let us take only this. This is inflow as a function of climb. Now, climb means I should be on the positive side; that means, this curve is applicable only for climb situation. As I keep increasing the velocity, what happens? This term (Refer Slide Time: 10:08) because velocity is V; nu H is fixed; that is, nu H is hover inflow. That is a constant quantity for the given rotor. As I keep increasing the velocity, this term will keep decreasing. Asymptotically, it will go to 0 for very high values.

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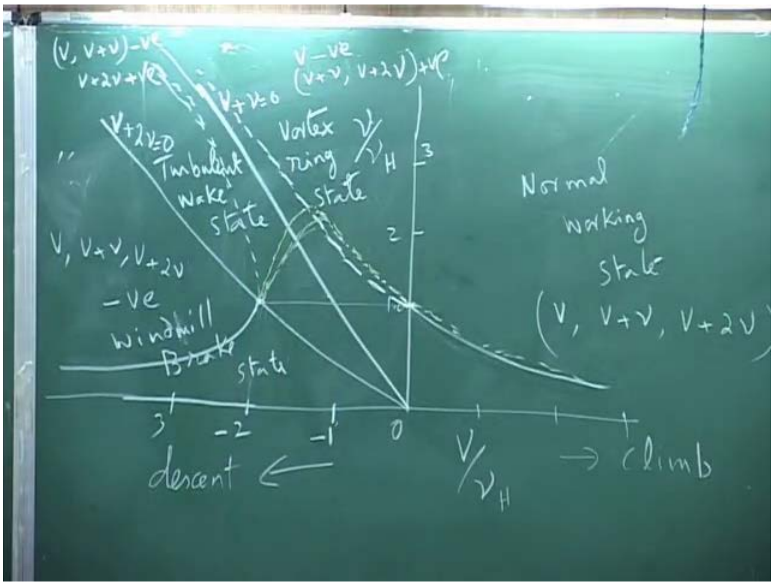

So, we will just plot 1 2 3; and nu over nu H in hover velocity is 0. So, nu over nu H is 1. So, the Curve starts from 1.0; here you may have 2; may have 3, etcetera. And, this curve will be like this. But, assume that this expression is valid even in the descent case. Then, V is negative, because I have to put V negative. Then, this becomes positive number; (Refer Slide Time: 11:24) and positive and positive; this will keep on increasing. So, I will just draw by a dash line. This is an extrapolated curve; that is, nu is always positive; please understand. When V is… Maybe I will mark here 1 and here mark 2; this is minus, minus and maybe it is 3. But, this will reach technically what? V by nu H; nu by nu H is V by nu H; both are equal, which means both are equal curve – is what? It is a 45 degree; this curve – asymptotically will go to this line. It is a 45 degree line; V plus nu is 0 on this line, because V is negative; nu is positive. So, V plus nu is 0.

If I extrapolate this to the descent, (Refer Slide Time: 13:13) the curve is going to be like this. Now, let us go and then plot; this is not… this is an only extrapolation of what is valid here. Let us plot the curve for descent separately. If you plot that… Let us take a slightly different… I will take this color. Now, let us look at the value, where it is. Suppose if V is negative; this value (Refer Slide Time: 13:47) – if V is 2 nu H, less than 2 nu H; or, V by nu H is less than 2, then this is an imagination number; that means, I cannot have a root; V is… I cannot have a root below this. I can draw one more line; I will just draw that. This line is V plus 2 nu equals 0 line. This is 45 degrees; this maybe slightly lower.

Now, the root will start only from here (Refer Slide Time: 14:58). And, I have two roots, because plus or minus; both are valid, because there minus is not valid, because inflow has to be always positive. Here I can have both plus, minus; both will give positive root, because this is always less than this quantity. So, I will have one line, which is coming like this; maybe I will draw slightly… (Refer Slide Time: 15:40) and the other root will go asymptotically to… So, for every value of this, you will have two roots: one of the roots will be above; one will be below.

Now, I have plotted this by continuous line; this by discontinuous line. Just to indicate, now, let us go back to this now; this is a problem. I should have drawn this figure there (Refer Slide Time: 16:21). Anyway it is OK; this is – V is positive; V plus nu positive; V plus 2 nu positive; everything is positive. So, this is normal working state – this quadrant. Now, when you go here in this, V is negative; nu is positive. And then, you will find that V plus nu is also… That is why this line is a border line for… This region is vortex ring state. In this zone, V is negative; V plus nu is negative; but, V plus 2 nu is positive here. So, this becomes – what is that? Turbulent wake state. And here, everything is negative; in the sense, nu; V is negative, V plus nu, V plus 2 nu – all of them are negative. nu is positive; please understand. Nu – this is always a positive quantity. What we are writing is V – these three; (Refer Slide Time: 18:45) all are positive. When you go here, V negative; V plus nu; V plus 2 nu – they are positive.

When you go here – (Refer Slide Time: 19:01) V comma, these two are negative, but V plus 2 nu positive. When you come here – V, V plus nu, V plus 2 nu, all are negative. And, this is windmill brake state. Now, you see the inflow diagram only in vertical flight, is expressed in non-dimensional form into four regions, but the continuous lines are valid. But, in between line here, these results are not valid. So, you have to only do some kind of a experimental estimation, because the flow is highly turbulent, mixed; you cannot get the inflow, because there is nothing like inflow at a particular point. That will be a flow, but you will not be able to get it; you will get some mean kind of a value. So, how do we do it? So, lot of experiments, theories; people are trying do something, but, it is a very tough problem, because the flow is highly mixed. In the experiment, they try to take a rotor and then try to design, bring it down, find out what is the power it has taken. From there you are somehow assuming that you will be able to estimate the inflow; please understand. Estimate the mean inflow – I will write that later.

Then, the curves show like this (Refer Slide Time: 21:11). Maybe I will a draw a different color. So, this is some kind of experimental. These are all theoretical curves. This yellow is an experiment. You do not get inflow somewhere here, but experimentally, measured means what inflow? It is only a mean value you can estimate. Now, how do we really estimate that? Because if you remember last class, I mentioned V plus nu is 0, means there is no flow to the rotor disk and the power is just very simple without the drag power. Just I am taking only induced power. Induced power is – we know that P induced is thrust into V plus nu. And, if V plus nu is 0; that means, I do not have any power, but (( )) rotor is generating thrust of T, but it was descending. This is called the autorotation, but technically, you do not take this particular velocity, because you have profile drag also. And then, tail may take some power and the fuselage also may get a little additional drag. So, usually, you design at velocities slightly faster than this point; (Refer Slide Time: 23:13) slightly faster than here; a little faster. You go a little this side. This particular Curve is the inflow curve; the same curve is represented in a different form. And, that form is the one which I showed you in the last class. Instead of plotting nu over nu H on the Y-axis, you plot the total flow through the rotor disk rather than only the induced velocity.

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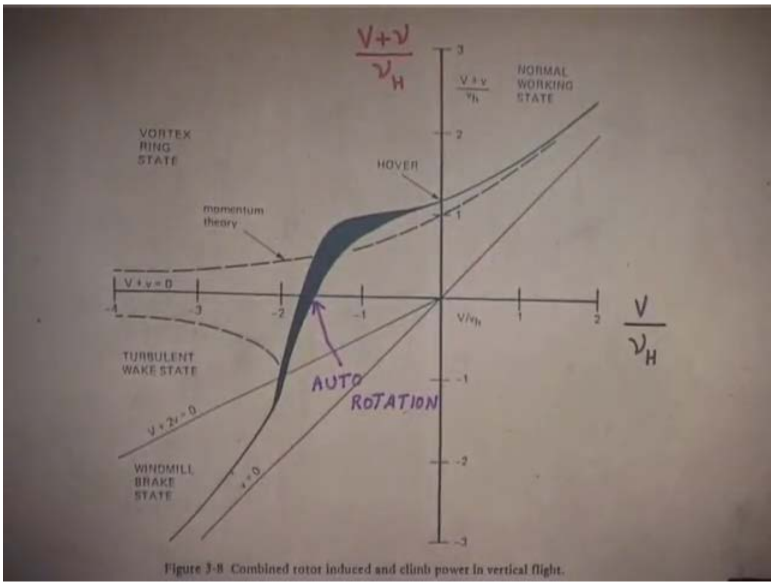

If you plot that, this whole diagram will get rotated. And, that is what I will show – this is the diagram. Essentially, we have rotated that original diagram a little now. In this diagram, Y-axis is V plus nu over nu h. So, I have added that. So, it is like 45 degree rotation. Now, you see V plus nu 0 is nothing but X axis. And then, it is 45 degree line, because V equal to… And then, this is V plus 2 nu – is this line. So, I have split the whole what I showed earlier – normal working state. This is the vortex rings state, turbulent wake and windmill brake state. Now, how do I… This is called the universal inflow curve. Now, how do I use it? Because you see very interestingly, this black patch (Refer Slide Time: 25:23). This is estimated, because you cannot do from this equation; please understand one thing. This equation is this dash dash dash; that is all. You realize – I can make an approximation in this zone; that means, the descent velocity – I will take… In this zone, I will do an approximation to say what is the inflow; that means, I am just going to assume some simple linear expression. And then, I will be able to arrive at… Basically, V plus nu – I can do that; I will show you what it is done. And, that curve you can use it for predicting any autorotation situation, because this is a very important curve. Even now some publications come.

How do I get this zone? Because this is one of the flight condition, because autorotation is a criteria, which the vehicle has to meet certain guidelines; that is, when the engine fails, what are the pilot should take a corrective measure. And, it should not come like a stone; it will come down. But, we will see – it will not come down very slowly, but it will come down some (( )) velocity; pilot still has a control; he will autorotate; he will come and then he will land without much damage. That is the idea, because this is one of the capabilities of the helicopter.

Now, you see this is not that easy (Refer Slide Time: 27:25). This region at the very simplistic level of introductory course itself, you will know that there is something which you cannot calculate. You have to… That is where the experience industry, test, measurements. Pilot go through a little bit of autorotation experience in flight; not that they will come and land; they do not do that. They will just do a power off and then try to do… because there are some maneuver they must learn. We will do a little bit on that, because autorotation is very interesting; pilots are taught much more in this, but we will not spend too much time on the autorotation. It is only one of the flight condition. What we will do is we will try to get an approximate line here and we will use that to see how we can proceed further. Is it clear, you have any questions? Because this diagram is even today, you have to make that approximation in that black zone. Some tests are done. You can get some data points, but can you predict theoretically? It is very simple; you have a rotor; the rotor is descending. Use a sophisticated analysis and predict.

Now, that is a very challenging task; it is not that easy. Now, that is because usually, we do not take which is a tail rotor power practical problems. You have power taken by tail rotor also. Those are not included when I write the power is only the main rotor; that is number one. We neglect swirl effects. Even though there is a small percentage, we neglect that. Non-uniform – these are all calculated based on what uniform inflow; what we said, non-uniform inflow may change the power and then swirl. Then, there can be transmission losses. All those things can be there, which about – see tail rotor take some power and then these losses are also there. So, that is why industry has an estimate. They will say total power; but, what we are doing is only the rotor power; but, non-uniform inflow – just rotor alone – even if you consider, I am not considering the transmission loss; I do not consider the tail rotor; tell me what power the rotor alone will have? Real power. Then, you find non-uniform inflow and then tip losses; and then, you can have swirl. So, these are all the additional effects, which we do not model in getting this curve (Refer Slide Time: 30:15). That is why practical curve – they just put it little; that is all.

Now, let us… Is it clear? Because this curve you we will have to use. So, I am telling you if you have any doubts, anything in understanding, you please ask me. So, this part is over, (Refer Slide Time: 30:40) because the utility of this equation is only to draw that diagram; that is it; there is nothing else. Now, let us say for that black patch –this zone here, (Refer Slide Time: 31:02) V by nu H is approximately 1.6 to 1.8 width.

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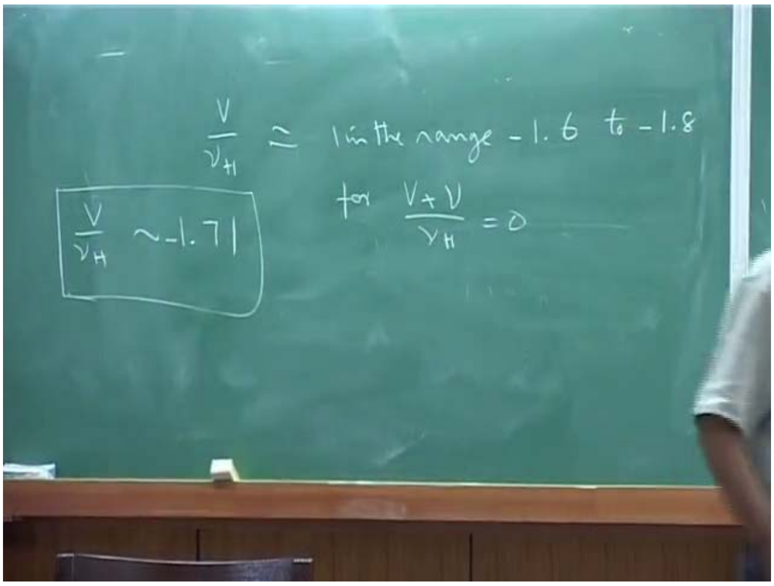

V by nu H in the range 1.6 – you can take it minus – to minus 1.8; please note – for V plus nu over nu H equals 0, because this is the zero condition. It is in that range. Usually, it is taken as approximately 1.71; somewhere midpoint for V plus nu; it is enough. In between these two, I am taking that point. I am going to… See it is a very steep line. So, I will draw a straight line approximation.

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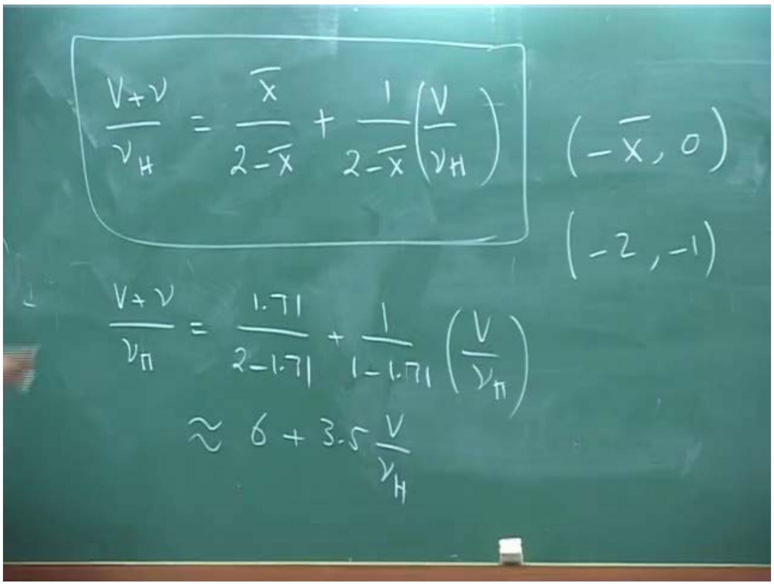

And then, write how V plus nu over nu H. If you take this point, I have to say the coordinate of this point; (Refer Slide Time: 32:40) you can write it as minus X bar comma 0. That is the co-ordinate of this point. Minus – I am already taking, because it is in the negative descent. And then, the coordinate of this point (Refer Slide Time: 33:12) – please note this is the point, because where I have both the roots come. This is the point where I start having root for the descent. Below that I do not know. So, the theoretical curve tells minus 2, minus 1 – this point. So, I will simply draw a straight line between these two points. And, the straight line will be what? I will write that equation; that is, (Refer Slide Time: 33:54) plus (Refer Slide Time: 34:00). This is the equation – straight line equation, because you just use Y minus Y 1 divided by Y 1 minus Y 2; X minus X 1 by X 1 minus X 2. This is just an equation. The equation of the line from here to here (Refer Slide Time: 34:24). And, if you use X bar somewhere between these number – because X bar is what? Basically, this. If I substitute 1.71 – it will be approximately, see divided by 2 minus 1.71 plus 1 by 1 minus 1.71 into V by nu H; approximately, this is written as 6 plus 3.5 V by nu H; that is all; you will find that if you want really… because this is not exactly 6; this is what 5.88 or something like that; this will be 3.4 some number. So, you take it approximately; this is the line.

Now, you know that I have inflow estimation in the turbulent wake state, because… Why I need an estimate curve? I can you can always say I can extend this curve (Refer Slide Time: 35:33) even here also; you can take it; it is fine. But, normally, people are not really interested in having this, because this is purely from autorotation point of view. Now, you see even when I descend very slowly, see this line – this is the line theoretical; it is slightly up, but it is all right. It is not that this is deviating totally off. So, I make a small error even in the other expression; but, it is OK; I can take that inflow if I am coming down slowly. But, you cannot use this expression completely even here, (Refer Slide Time: 36:24) because this line will go like this and that line will come like this. So, you can have some kind of an approximation; that means, I know the inflow even… But, this inflow – mean inflow, because I really do not know what exactly happening everywhere in the zone of vortex ring state and turbulent wake state; just approximation. And this you can use it for evaluating power or anything like that.

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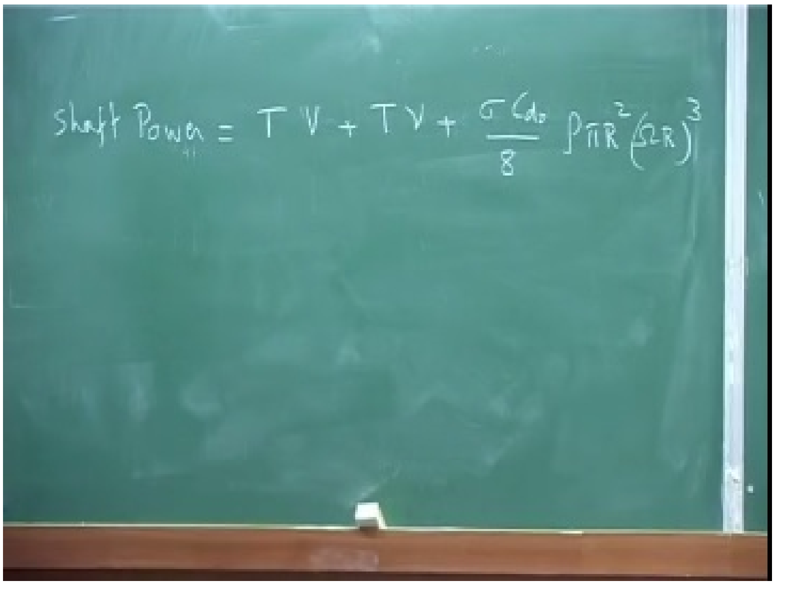

Now, I will see how you can really use, because the shaft power is essentially to rotate the rotor and you are descending with a thrust. So, you can say the shaft power. This consists of three components we had. One is the climb – it is Climbing with the velocity V; climb or descent; it does not matter; T V plus T nu plus the profile drag, because that is… At least we did this; that is, (Refer Slide Time: 37:45) sigma C d naught by 8 rho pi R square omega R cube.

Actually, true autorotation means this power must be 0 (Refer Slide Time: 38:04). True autorotation, because you have this; that is why the velocity with which it descends will not be at the point V plus nu is 0; it will be slightly at an increased descend velocity (Refer Slide Time: 38:26). It will not come at 1.71, where it means V by nu H; it will be slightly more, because you need to cancel this term also. Actually, this kind of expression is used to estimate, because you take a rotor; you try to descend; slowly, you find out what is the power you require; then, you can get approximately from there if you know this quantity, this quantity, because thrust is known; you know V. You can make an estimate of inflow; estimate mean inflow – it is very crude. And, that is how those dark patch.

Now, you see these are all (Refer Slide Time: 39:19) for basic climb and descent. Hover is wonderful; climbing is fine. But, the moment you start descending, problem starts; but then you need to have an expression to evaluate quantities; and these are all the expression that is used, because industry will have some approximation; that is all. And, that will be based on this kind of curve; this is a universal inflow curve. And actually, this was drawn; I would say 19… I will show 1947; an alternative by lock – that curve – this is called the universal inflow curve. So, please understand, because the moment the problem becomes complex; see one is you have to go deep into the physics; start analyzing it very systematically; but, otherwise, with what you know, you try to have some approximate, but physically, meaningful expressions. And, the physically meaningful, which is useful – that comes by practical experience. And, that is what these type of curves are; you will slowly realize in this course – enormous approximation are made everywhere, because you cannot just handle things, because this itself is a problem; you can do a PHD on this. Even today you know CFD; I am going to model, because rotor CFD is still at the primitive stage. It may come up in future; get the rotor inflow; I want the rotor inflow when the rotor is descending; very simple case; get it. And, theoretically, predict this. If good, you will get your PHD.

Now, let us look at some pure numbers just for the sake of interest, because this is an interesting part. We said V plus nu 0 is good. This is slightly little negative number. But, what is really the descend velocity for autorotation in practice terms? The descend velocity. And, if you really look at it, (Refer Slide Time: 42:12) we said that very crude approximation; this line meets somewhere around 1.71 we used, because in the range of 1.6 to 1 8, we took that 1 minus 1.7; that means, V – very crude approximation. Please note that this equation you take it, because this is important (Refer Slide Time: 42:38).

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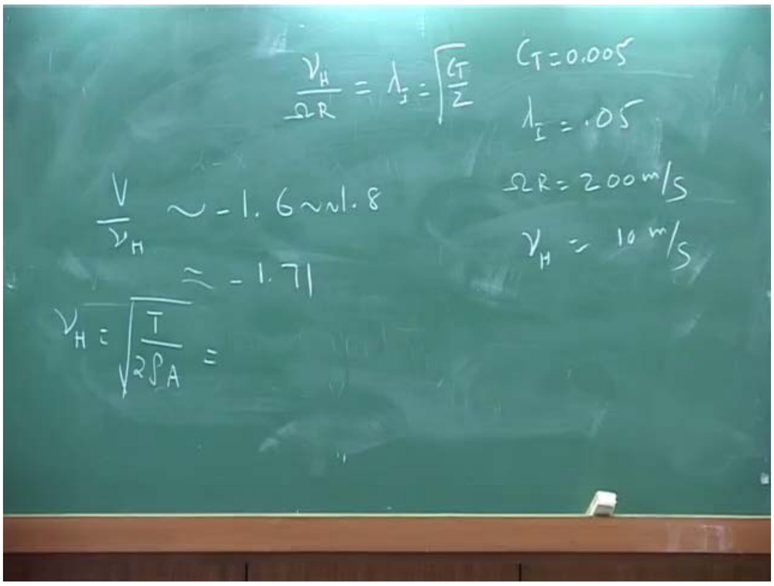

So, we said V over nu H in the range 1.6 to 1.8; or, you take it approximately 1.71. Now, you can know nu H; nu H is what? Square root of T by 2 rho A; or, in other words, you can take it as what? C T by lambda. What is lambda? Nu H over omega R is lambda I, which is square root C T by 2. And, if you take C T, most of the rotors – you can take it approximately C T as 0.005. This number is 0025. So, lambda I will be 0.05; and, omega R, tip speed – you can take it as 200 meters per second. Therefore, nu H will be 10 meters per second if I multiply; V is the descent velocity. So, it is negative number. You will find it will be coming with word 17 meters per second; so, in the range of 15 to 25 meters per second it will come (( )). It is not, then it will come very slowly like a leaf – 15 meters per second is quite substantial in autorotation. But, what pilot comes? He will not come and then hit 15 meters per second or 20 meters per second in the ground. He will come near the ground and then when he comes near, then he will try to climb up; that means, he will increase his collective and then he will try to… It is called flare up. So, he will come and then he will try go up; and then, he will slowly land.

This is a vertical; (Refer Slide Time: 45:19) please understand this – whatever we wrote, is autorotation in vertical descend; but, you can autorotate in forward flight also. Actually, they try to autorotate only in forward flight; they do not come down like this, because you know that this is the shaft power. Suppose if the power required for a given flight condition is less, then automatically, you will also come down with a less speed. That is why you autorotate at a forward speed, where the power required for flight is minimum. Therefore, you autorotate in that particular speed, because that part comes a little later. Right now, this is only vertical up and down motion.

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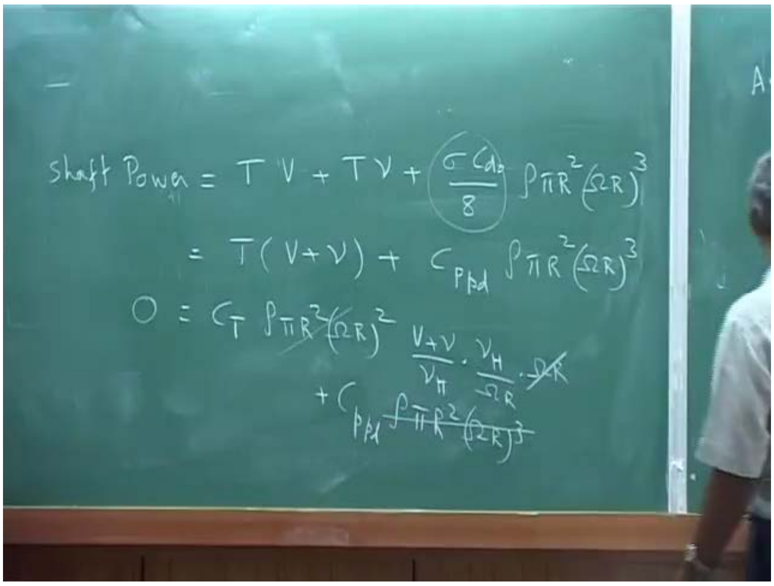

Now, just for some interesting part, we will take even this itself. This is T into V plus nu plus – I combine all these things as some C p profile DRAG – rho pi R square. And, this I can replace by C T rho pi R square omega R whole square into V plus nu over nu H into nu H over omega R into omega R; I am doing lot of non-dimensionalization just to get some interesting form (Refer Slide Time: 47:37) rho pi R square omega R whole cube, because I multiply by nu H divided by nu H; and, omega R is non-dimensional. Then, what will happen is this is V plus nu over nu H; you will find that rho pi R square… if I said this shaft power for autorotation.

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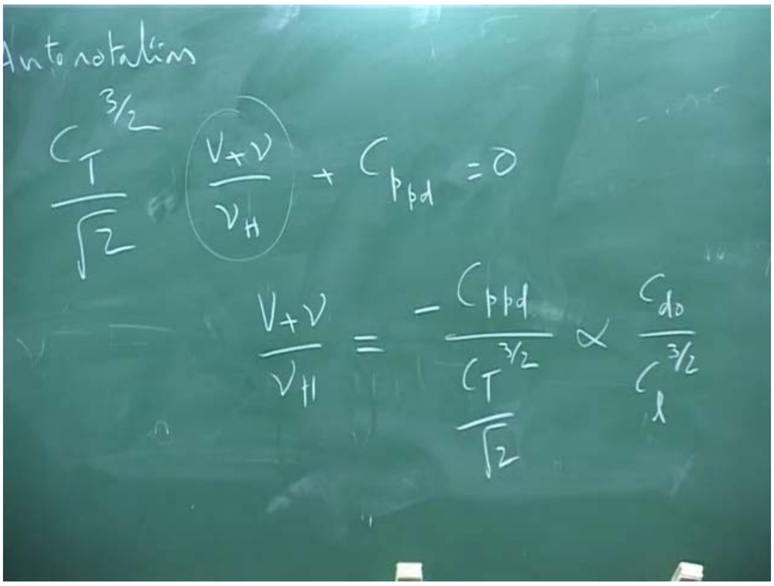

Autorotation condition – power must be 0. So, this term will go off; this entire term will go off (Refer Slide Time: 48:16). And, this is lambda induced, which is root of C T by 2. So, I will get here C T to the power 3 by 2 over square root of 2 into (Refer Slide Time: 48:41); that means, V plus nu over nu H is nothing but minus C p – this is the profile drag whatever all the drags – C T power 3 by 2 under root 2. Now, you know that as a proportionality, this is nothing but C d naught; profile drag is proportional to drag coefficient; thrust is directly lift coefficient.

If you want to have a low descend velocity; if this term (Refer Slide Time: 49:47) is less; C d naught over C l power 3 by 2. This also relates to the airfoil characteristic. If that value is small, that means the autorotative descend velocity is also small. And, that is how in the selection of airfoils for… because it is not then one airfoil you can choose, because the rotor blade is a long blade say every section. But, this is one of the interesting part where… And, you will find that if you normally substitute the values of C d naught over all these things, this is approximately around (Refer Slide Time: 50:36) minus 0.3, 0.4; 0.3 – something like that; that means, V plus nu over nu H is about minus 0.3, 0.4, which is – this is the Y-axis (Refer Slide Time: 50:53) – V plus nu over; that is around – this is 1, 0.3; maybe somewhere here. So, you are descending at this velocity. So, you can get from this value.

Now, you see, you will be descending with a lower velocity V if this quantity (Refer Slide Time: 51:17) is small. Now, you can plot the curve of an airfoil C d naught; drag coefficient over lift coefficient to the power 3 by 2 for various angles of attack. And, that will tell you what is the minimum angle of attack you should operate, because if you operate at minimum angle, that curve I will show, because this is a very interesting part, because efficient angle of attack for autorotation.

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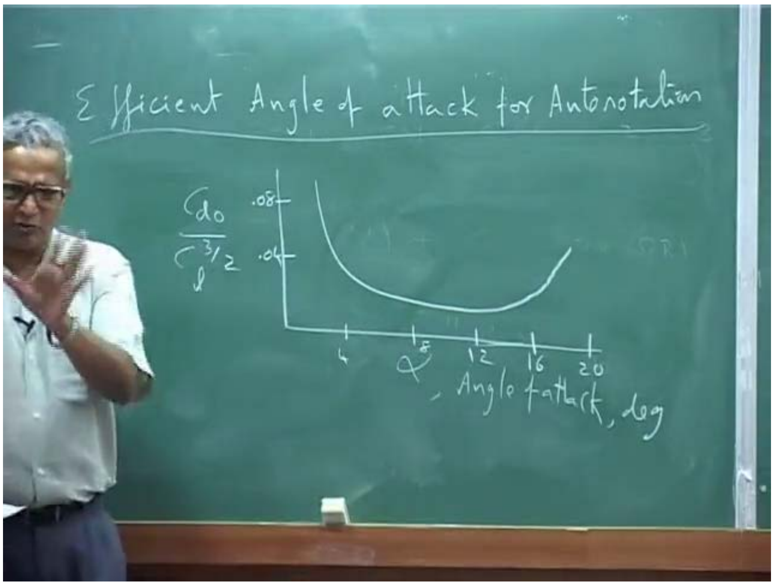

So, you know that this is the one; see this is an efficient angle of attack for autorotation. When you say efficient you want minimum… See you do not want to come fast; you want to come slowly; then, you can land very safely. So, you want to come slowly means I can come slowly if this quantity is small; that means C d naught over C l. So, I will plot a curve for… This is C d naught over C l power 3 by 2 as a function of – this is angle of attack. You can plot only for airfoil this; one airfoil, because rotor is not… because every section.

Now, you see if every section has to operate efficiently, how you have to design the rotor. This curve will like be this; (Refer Slide Time: 53:17) I think this is 0.08; I think 0.04; here this is in degree – 4, 8, 12, 16 and 20. The curve will come something like this; it will go like this. So, you have a fairly wide region for…, but below stall. If you go 2, again you will go; this is stall if you higher angle of attack. If we come too low also, it is not good. So, there is a wide range of operating condition for airfoil. This is from the characteristic of the airfoil; you have to draw that line. Now, there is another interesting aspect also, which is related to… How do I… What is that angle? Because helicopter is flying; engine fail, because pilot would have given a pitch angle assuming he is hovering – collective pitch he has given; the blade is operating at a particular pitch angle; please understand pitch angle; not angle of attack.

Now, engine fail; he has to autorotate; what pitch angle he should have? If he has a larger pitch angle, the drag will be… So, there is a diagram, which is a very interesting diagram. That is purely based on forces acting on airfoil in autorotation; please understand. But it is again a very simplistic approach; not with all the turbulence and vortex, etcetera; very simplistic formulation. But, that curve is used for practical operation. But, that is a very interesting curve, because autorotation – if you really see, it is an equilibrating situation.

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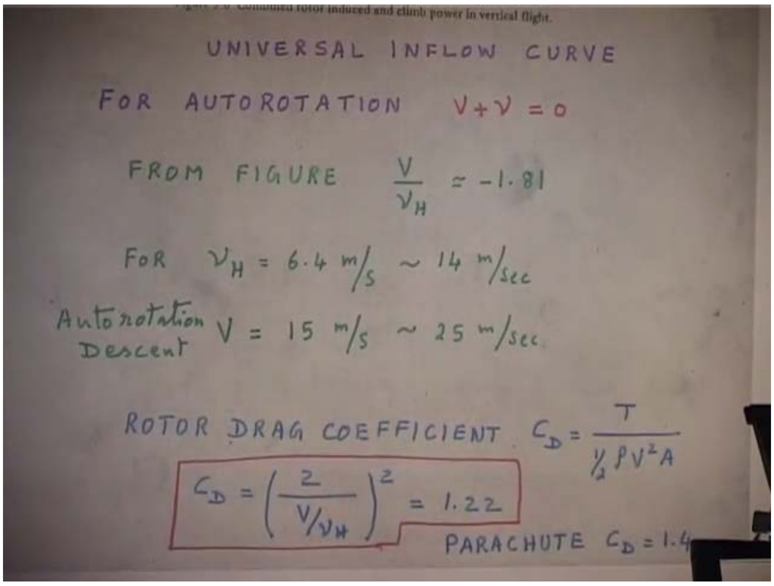

So, I will just show that part and I also mentioned; this is just for… since you asked drag. What is the drag coefficient? Because rotor is rotating; thrust is acting up. Thrust is there and this rotor is coming down with the steady velocity; please understand. When it is coming at a steady velocity means what? That means, that drag force; the thrust is basically the drag force. And, this is the thrust, (Refer Slide Time: 56:37) which is… Actually, this is coming down; that is the force. So, the drag force divided by – what do you normally write? Dynamic pressure area into some drag coefficient.

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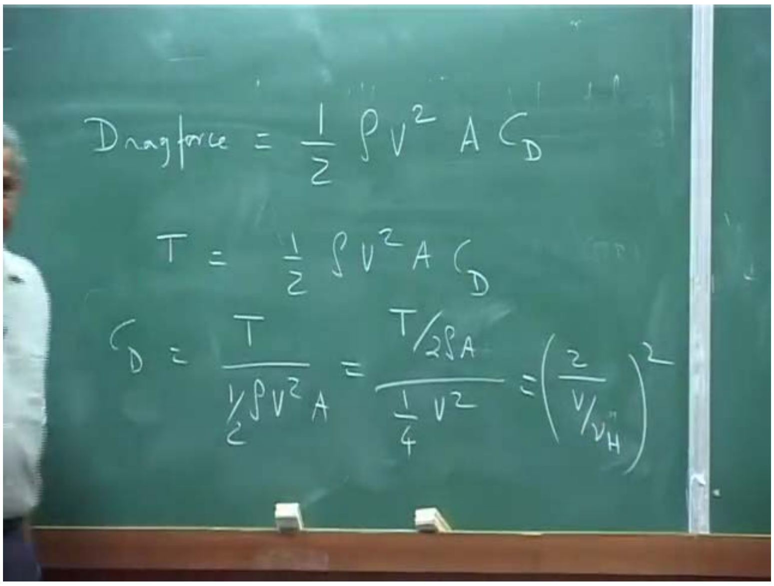

If you write that, the C D, because that I will show you how that expression came about, because, normally what you will write in drag force? Drag force is written as what? Dynamic pressure – some area into drag coefficient. If it is a lift force, you will put lift coefficient. Now, the rotor is coming down. So, what is the force? Force is thrust; thrust is acting. So, I will put T equals half rho V square A C D. Now, C D is – that is, I am calculating the drag coefficient of the rotor. This is nothing but T over half rho V square A. You can write this as T over 2 rho A over 1 over 4 V square. This is nothing but nu H. So, you will have what? 2 over V by nu H whole square. Now, you know that V over nu H. It is around in the range of 1.71; 2 divided by 1.71; you take it; put it there; the drag coefficient will be of the order of see 1.71 (( )) 1.22; somewhere around 1.2, 1.3 in that zone – drag coefficient.

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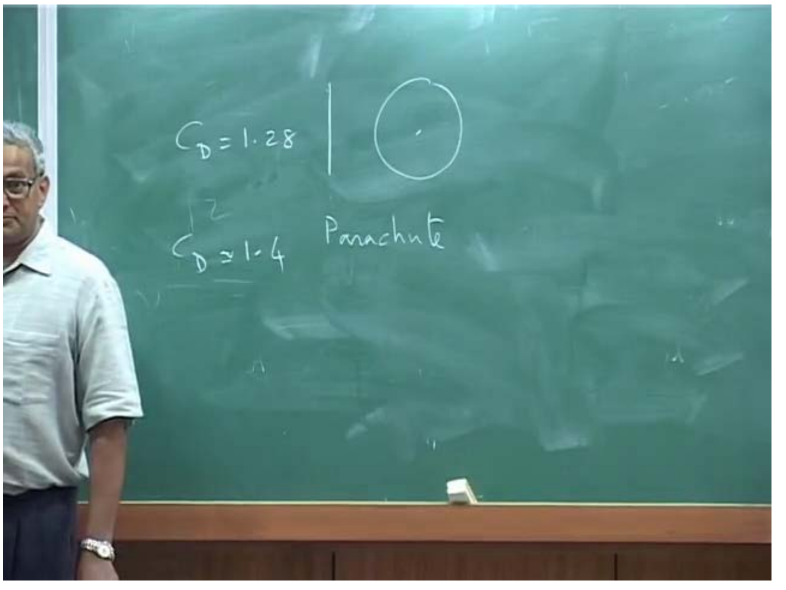

Now, I will just read out the drag coefficient for actually a circular plate; that is, solid with an area A; its drag coefficient is 1.28 – circular plate. So, a plate – this is a circular plate. Its C D is 1.28. But, if it is a parachute, that C D is 1.4 approximately.

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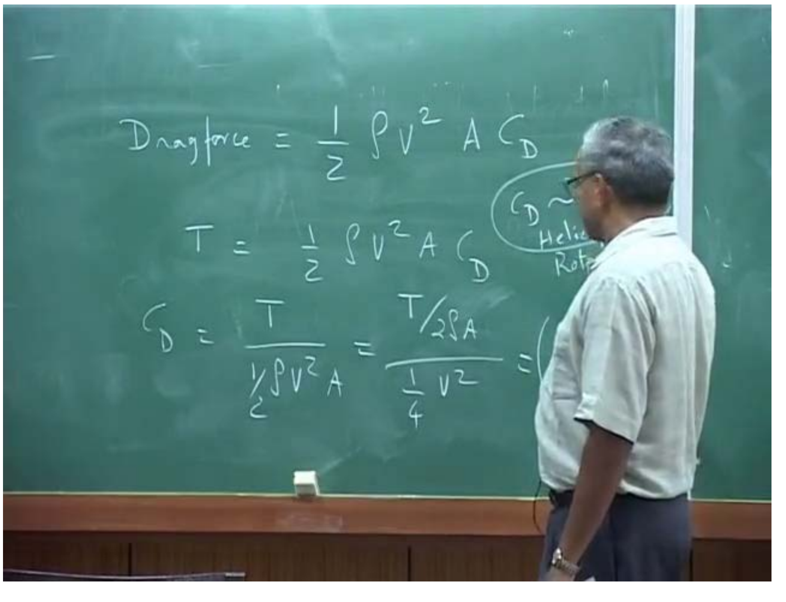

And, for this, it is around 1.2 to 1.3. C D for the helicopter is in the range of (Refer Slide Time: 59:52) for helicopter rotor. So, you see it is power of vertical design; the helicopter rotor behaves like a parachute, but of the same area, because the area is… If you make it a big one, then it will generate lot of force. So, it is a very efficient in autorotation.

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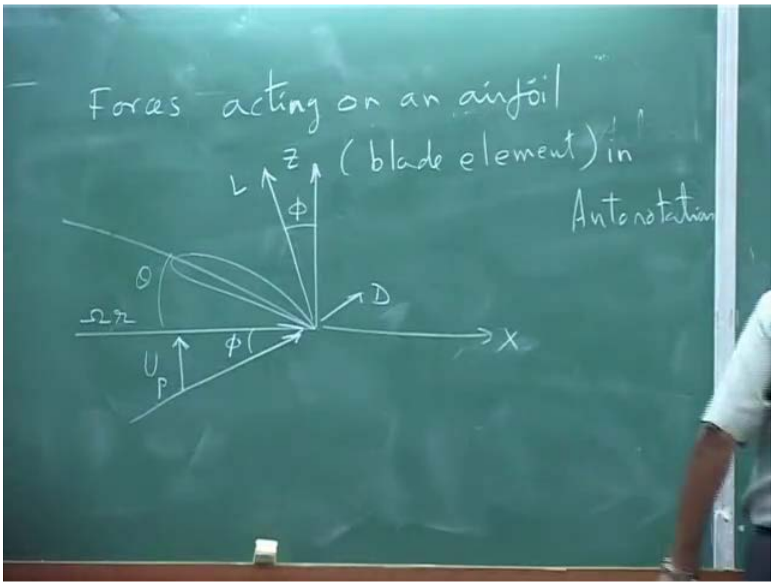

Now, let us take… This is another interesting aspect of autorotation. That is like I told you; he is flying at a pitch angle; engine fail; what should we do? By drawing a airfoil we will analyze that part. I will just draw today; I may not be able to complete it; that is, forces acting on an airfoil, which is coming down; that means, essentially, I am taking a section or you can say a blade element in autorotation. I will first draw the diagram. You have the airfoil; that is a… This is omega r. This Angle is theta; that is a pitch angle pilot has given. But, it is in autorotation means this is coming down. Let us say it has U perpendicular; I have drawn it up. Now, the resultant velocity is this (Refer Slide Time: 1:02:39). So, this angle is phi. Now, let us draw. You have – this is the Z-axis; this is the X-axis; lift is normal to the resultant flow; this is lift and the drag is along that. So, this angle is again phi.

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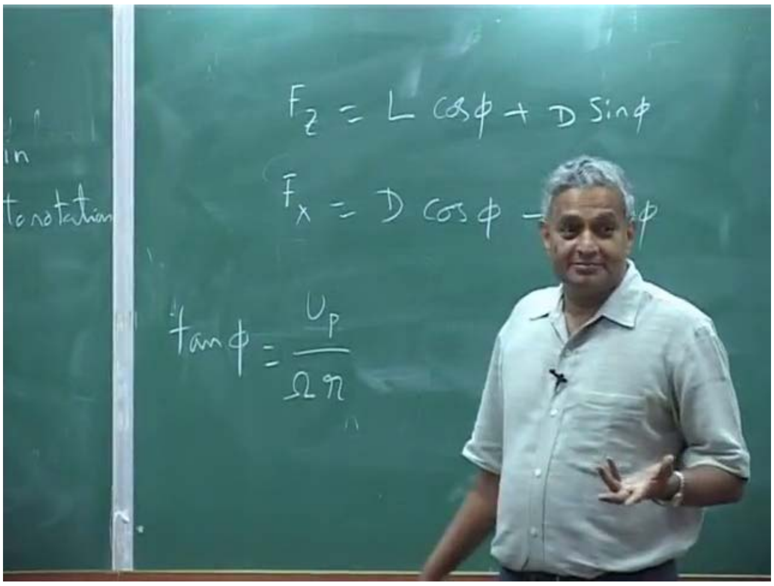

Now, what are the forces acting on that? If you take the forces, the forces acting on that is, F Z is L cosine phi plus D sine phi; and, F X is D cosine phi minus L sine phi. Till now the rotor is given a power. Now, the power is gone; engine is disengaged. Now, what will happen? This will be rotating because at the instant, you will have omega R and the rotors descends. This is (Refer Slide Time: 1:04:15) the velocity U p. And, the lift drag. F Z is actually the weight of the helicopter; that is, the thrust you can say. I am drawing for one section, but basically, you have to integrate over the entire blade.

Now, what will happen is – if F X is positive, then what will happen? Because there is no Power that is given to the blade and you are having a force in the X direction; airfoil is moving like this. But, you have a force. So, it will try to stop. It will start decreasing its velocity. On the other hand, if F X, whatever that is written, if it is negative – negative means that force is here, it will accelerate… because there is a force; it will accelerate the airfoil. So, there is a particular angle – that phi – at which this quantity is 0; that means, there is no force acting on the airfoil in the X direction. X is this (Refer Slide Time: 1:05:49). When you have no force, whatever the velocity it has, it will continue to have that velocity. And, that is the condition for the autorotation. You have to get that phi.

Now we will relate to what is that theta, what is that phi, how do we get that; that – we will look at that diagram. Now, the interesting part – I am just throwing it. This is for one section of the blade. The rotor blade is rotating with the omega R, which is varying;

every section is different R. Even if I assume U p is same, near the root what will happen? Omega R is… because what is phi? Let us write the phi; what is tan phi? Tan phi is what? (Refer Slide Time: 1:06:53) U p by omega r near the root; this is small; that means, what? Phi is large means what? If they have a large angle of attack, what will happen? It will stall.

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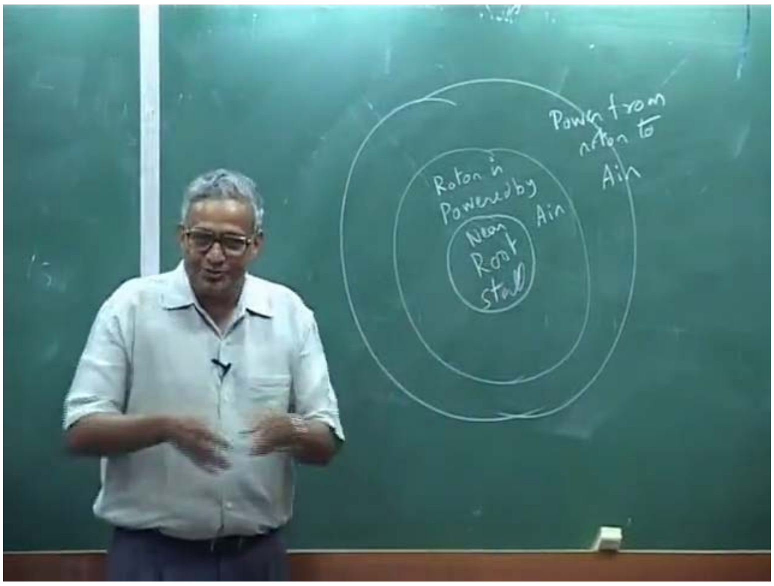

Now, let us draw the diagram, because if I draw… because I am drawing the diagram; later, we will… This is the near root. It will stall; that is all, because angle of attack is large. Now, as you keep increasing omega R, what happens? Phi is decreasing; phi decrease means what? This is coming like this; (Refer Slide Time: 1:08:08) from a large value, it is coming slowly; that means, it can come to the condition where autorotation is possible; that means, it is like not that every point is under autorotation. So, there will be one more circle, which I will draw. Here rotor is powered by air basically; that means, the resultant flow rotates the rotor. So, power from air to rotor. Outside, what happens? If you keep one increasing omega r larger, that means, the drag is more; that means, it will try to stop; that means, what? Drag is there means I am actually pushing the rotor. So, there is a drag force.

Air is pushing the rotor in the middle region; rotor is actually dragging. So, this is (Refer Slide Time: 1:09:38) power from – it is a normal operation – power from rotor to air. This is what the actual operation is. Now, you see only at one particular point somewhere in this whole diagram, one section of the airfoil will have that F X equals 0. It cannot have all points. It is very difficult to have that condition established.

Now, you see in autorotation, it is essentially the integrated effect of this (Refer Slide Time: 1:10:29). Integrated effect – that means, outer region – actually, I am dragging the rotor; that means, I am wasting power. Inner region – the air is pulling the rotor; to inside – it is stalling. That is why near root, it stalls means even though it stalls, you know the root cutout, every region is there; so, you will say I neglected now; it does not create much lift or anything like that; that is the region. Now, you see why they neglect that; I gave you 0.15 in their homework; root cutout – throw it. This is the region.

Now, the integrated value of air is pulling in this region (Refer Slide Time: 1:11:17). There rotor is actually getting that; net value is 0. That is autorotation; that means, the rotor blade will continue to rotate at the same rpm. Now, what is best rpm, because if you increase the rotor rpm, because the design rpm maybe for some particular value. Suppose you say I rotate it faster; centrifugal force will become tremendously high and blade may tear off; that means, you do not want the rotor to get lot of power also from the air; but, at the same time, you do not want the rotor to stop also. But, at the same time, you need to rotate at a nominal rpm. Now, this itself is a very challenging problem; it is not that easy. If you say I want to have a rotor very simplistic to whatever you have learnt, I say I am going to calculate the full thing. What should be the angle? Which is the best I must operate? We can do simplistically from this diagram, which I will do it next class, because if I start that, that is a very interesting thing; next class I will do. But, this is mainly for… do not thing that… Autorotation – you must know – power thrust – that T. This is more of physics; the physics is beautiful physics. But, it is not that easy. My dear friend, this problem is all.

Now, you see a rotor blade, which is pulled somewhere in the middle and pulled back somewhere; now, you see how it will deform, because in… So, you have to design the rotor blade also like that. It is not a rigid blade; it is a flexible blade. It will start getting a deformation. Now, these things go a little complicated. So, we will not get into that complexity right away. But, there is something which pilot is instructed; when the engine fail, what he will do? His job is to reduce the collective, because if he has more collective, that is this angle; (Refer Slide Time: 1:13:40) he may stop the rotor. We do not want to stop the rotor. And, there is again some operational restrictions.

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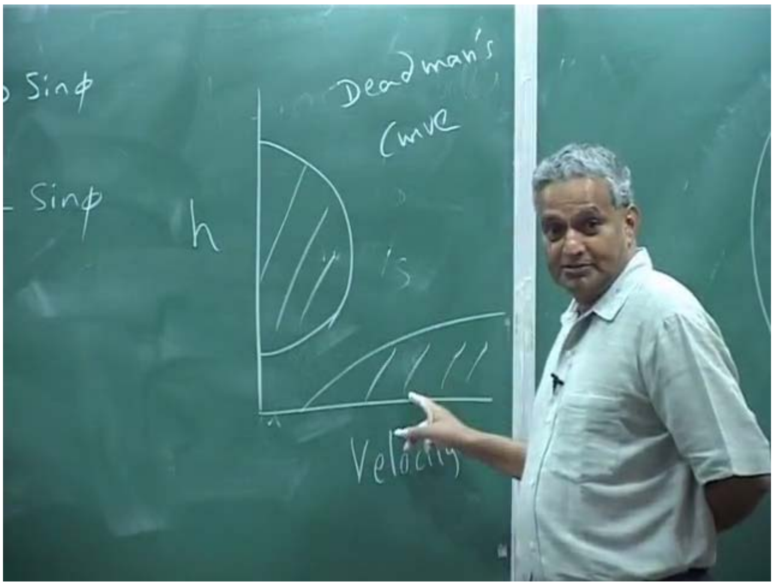

There is something called… I will just show – height, velocity. Helicopter can hover – beautiful; that means, 0 velocity; I should be able to operate at any height. But, they always draw something like this. Do not… This is called Deadman's Curve, because if he is somewhere here, if engine fails, he does not have sufficient time to get into autorotation; whereas if he is above, yes, he can get into autorotation. And, if he is… forward speed, yes, he can. If it is too low, if it falls, he can have the height to autorotate. That is why this diagram is drawn; pilot never goes and then (( )) even though the capability is there; please understand. You do not do those kind of operations. These are all from handling practical application point of view. So, we will take this diagram. I will briefly explain next class. And, with that vertical is over. So, you know hover; you know vertical flight.

Next topic is the forward flight. But, forward flight will run for several weeks and that will be the real aeroelastic problem.