Design of Fixed Wing Unmanned Aerial Vehicles
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Lecture – 13
Climb Performance, Engine Sizing and Power Plant Selection

Good morning friends, welcome back in our previous lecture, we estimated what will be the thrust requirement or what should be the thrust available from the power plant or the power available from the power plant. If it is a propeller driven aircraft at different velocities right that means what are we doing here.

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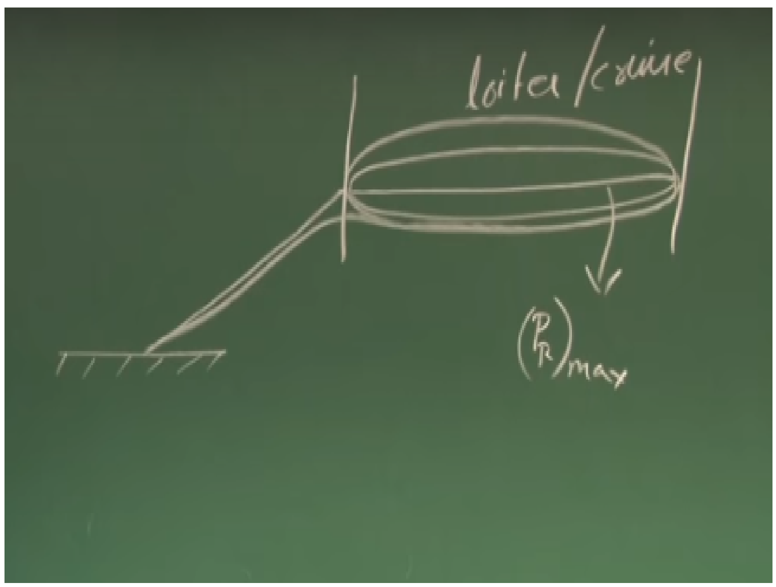

We are trying to perform Engine sizing right so if you look at a typical profile of machine profile of UAV what it has to do is. It has to climb to a particular altitude and then say cruise or say loiter which effectively is a cruise here and then decent to the home right. So, this loiter is performed by cruise right. So, what we have estimated is what should be the minimum and maximum power requirement.

Or the power requirement maximum for this particular profile right. So, say for this particular cruise we were able to estimate what is the maximum power requirement which depends upon the corresponding velocity per power required or say maximum it depends upon the maximum velocity of flight right. Say we have V max and the corresponding power requirement maximum so from here we are able to select one number.

From with which we can actually select the power plant right. So, this will be one of the criteria for selecting this power plant. At the same time which should also look at the other phases of flight say here we have rate of climb or what we called it as climb phase. And so we should also look at the power requirement during this climb phase. So that the overlap of this if you plot this power requirement for climb as well as power requirement for cruise.

So, your power plant should be able to deliver the power that is required it should satisfy both climb phase as well as loiter phase. Which means it has to deliver the power that is required during the climb phase as well as the loiter or cruise. Or say whatever I mean during the surveillance phase of this. So, we should also understand the requirement of this climb phase at the same time we should know how this power requirement changes during this climb phase.

What are the parameters on which this power requirement depends upon so that you can corresponding select the engine right? So, finally whatever the engine that you are going to select should satisfy the requirement of this climb as well as cruise phase. Now let us look at what is this climb cruise we know L=w and T=D drag right which we derived from general equations G1, G2 and now let us go back to G1, G2.

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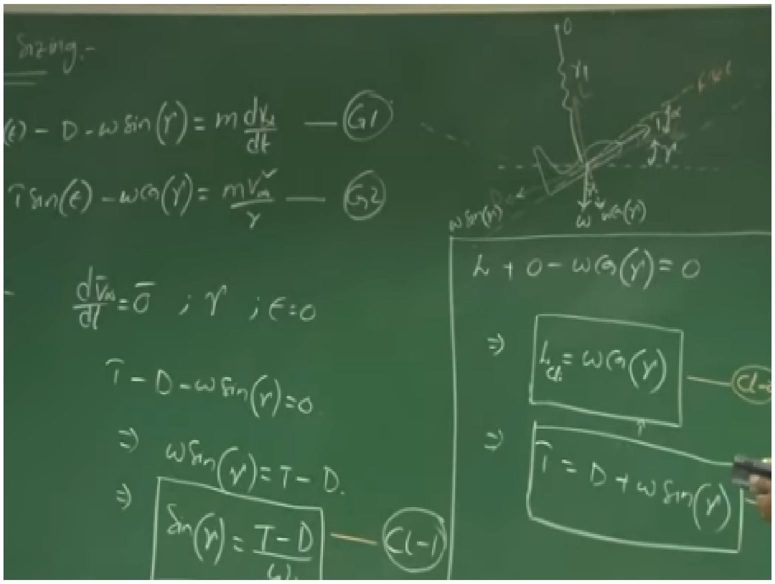

So, when we move this UAV at a particular velocity so we have lift acting perpendicular to it and drag acting along this V infinity right. So, due to weight of this system acts perpendicular to the local horizontal so this flight is moving at an angle gamma with respect to this local horizontal. The corresponding component of weight perpendicular to this V infinity is w cos gamma.

Where this is gamma and the component of weight acting along V infinity is w sin gamma and there is a thrust misalignment epsilon right with respect to free stream. Now what we derived is equations of motion along and perpendicular to flight par. Which is T cos epsilon -D-w sin gamma=mdv/dt right so this is our G1 and the other equation is L+Tsin epsilon-wcos gamma=m*V infinity square by r.

Where r is the corresponding radius of turn and these are the equations of motion in the vertical plane right r1. So, say this aircraft is performing a loop in this vertical plane. Now let us look at a steady climb so as the name indicates it is the study where acceleration is 0 right and you have gamma since it is climbing. And further assume that epsilon is 0 this you have might already done in performance course right.

So, let us look at the corresponding power requirement with the help of this equations and now this G1 and G2 reduces to the following by with the help of these assumptions T-D-w sin gamma=0 and which implies w sin gamma=T-D alright which implies sin gamma=T-D/w. Let us say this is our climb this is climb right study climb C1 or say CL1 climb 1 let this be CL1. It should be CL1 now what about G2.

Substitute these assumptions in G2 what we have here L+ 0-w cos gamma=0.This implies L=wcos gamma this is climb CL-2 climb 2 equation for second equation for climb and this is first equation for climb right what do you absorb from here. So, this I can rewrite this equation right. This equals to T=D+w sin gamma right in case of cruise we have T=D and L=w so the lift requirement during climb is < the lift requirement during cruise.

Right because this is for climb CL, CLi right what is CL for cruise and CLC is w if I divide these two what I have is CLC cos gamma lift for climb=lift for cruise*cos gamma which means lift for climb is less than the since cos gamma the limits are <=1 right maximum value of this cos gamma is. So, when this cos gamma will be 1 when gamma is 0 that means that is the maximum case for this particular equation is cruise.

So, lift for climb is < that of cruise but say with the same aircraft we want to cruise and we want to climb that means weight of this aircraft assume to be let us assume the weight of aircraft is same. Since the lift is less in this case but who is balancing the rest because the weight is same we need to produce lift = weight not to have this practice thrust is taking the additional load here. In case of cruise simply have T=D.

But in case of climb we have another component w sin gamma yeah this is the additional component so when this additional component will be 0 when gamma = 0 right when sin gamma will be 0 when gamma is 0 that means if you consider gamma 0 flight which is the level flight. So, we already have a study condition here and it becomes a study level flight. Climb will become a study level flight in this case.

So, that means so you need to produce more thrust compare to that of L level flight here while climbing. So, this additional weight is taken by the engine right. So, the engine will lift the additional weight here in this case or the power plant so CL3 climb 3. So, what does it mean here sin gamma= T-D/w.

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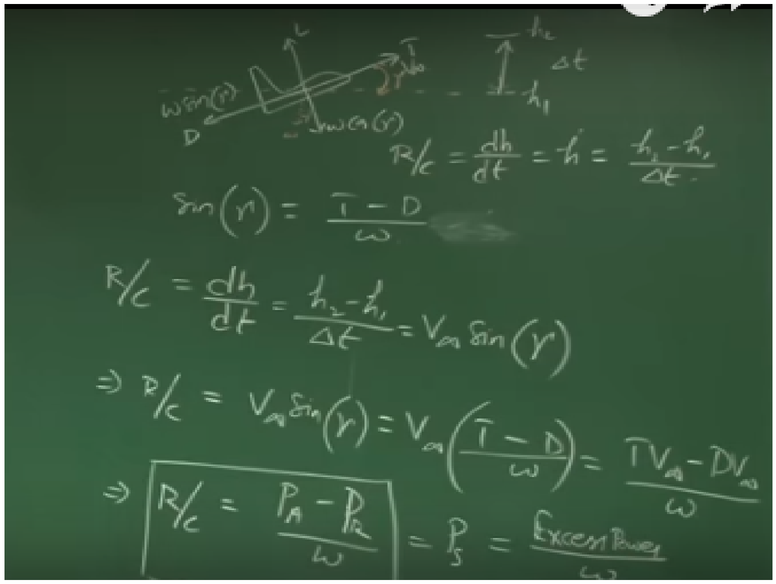

So, say for the study climb with these assumptions we have thrust and we have V infinity and what we have is draft and we have w sin gamma lift and we have w cos gamma right. This particular angle is the climb corresponding angle of climb ground. So, this is the vd for this particular case so this gamma is the climb angle given by T-D/w right. So, what are the factors that affect this gamma say if I want to reach a particular altitude say h2 from a altitude to h1.

So, how fast I will reach this altitude right is known as rate of climb so say I want to reach within a time delta T right. So, how fast I reach from altitude h1 to h2 is given by dh/dt which is h. here is a h2-h1/delta t. See what is h2-h1/delta t it is a component of velocity in this vertical plane along the vertical axis right. So, this component of velocity along this vertical axis is known as rate of climb R/C.

Right now we have V infinity here along this we have c infinity of this aircraft right inclined at the angle gamma what will be the component of this velocity in the perpendicular direction perpendicular to local horizontal or what is the component of V infinity along the vertical axis. This is V infinity sin gamma right I am correct or not? See what we have we define rate of climb which is the vertical velocity right which is h2-h1 /delta t right.

So, this V infinity has the component along the vertical direction do you accept this since we are climbing at the angle gamma. The component along this vertical axis is V infinity sin gamma =V infinity sin gamma. So, what is sin gamma rate of climb= V infinity sin gamma=V infinity T -D so this is from the equation climb 1 that is CL1. CL1 says sin gamma is T- D/w simply substitute T-D/w here.

This implies T*V infinity –D*V infinity/w so if you see there is a climb whenever there is a climb there is a corresponding angle climb angle. This is possible only when you have some additional force dont you see this. What is T? TV T is the thrust supplied right from the engine it is the output from the engine and D is the requirement of the system. So, D is a requirement of the system of this UAV and the drag is the required force like the drag should be.

An equal and opposite force need to be supplied to the system for a level flight condition but in case of this for a climbing flight you have to produce bit more force right. So, drag is the requirement of the system here so T is the output from the power plant D is the requirement right that means this difference is the excess thrust. If say D is the requirement and T is the available thing so difference of this the is the excess thrust that is available.

So, this is known as T-D/w is known as specific excess thrust so gamma climb angle depends upon this specific excess thrust. Similarly, here TV infinity is a power available from the system and D to V infinity is the power required by the system and this we have already discussed previous lecture the rate of climb=power available-power required/w right. So, this is the specific excess power.

The difference between this available power and required power is known as excess power or /w is known as specific excess power. So, this depends upon the rate of climb depends upon excess power higher the specific excess power greater is your rate of climb right.

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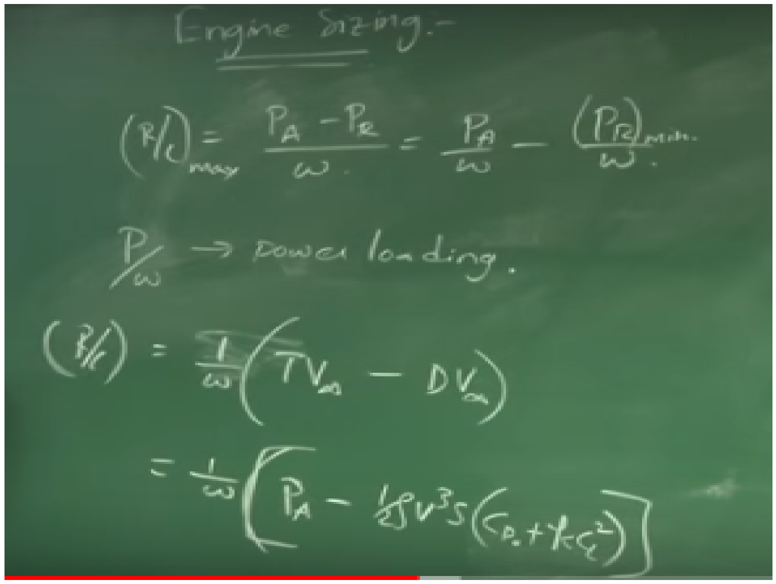

So, rate of climb = power available – power required/w right and this I can express as so one more term to introduce is this is ratio of power avail power to weight is known as power loading. So, rate of climb is depends upon this specific excess power so for the maximum rate of climb I need the minimum power required. Can we prove that so what is the rate of climb there rate of climb=T/w- or say 1/w times.

T*V infinity- D*V infinity= 1/w T*V infinity is the power available – 1/2 rho V cube s c D0 + kCL square right.

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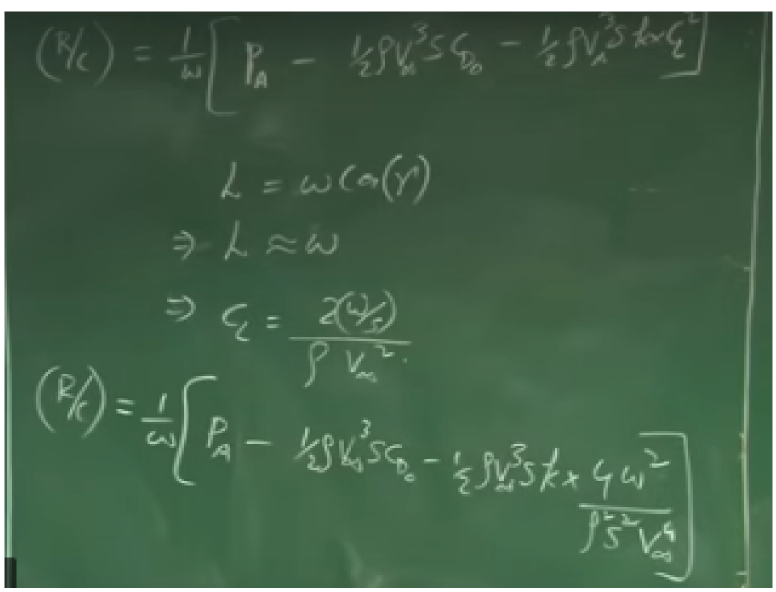

So, rate of climb=1/w*power available– 1/2 rho V infinity cube S*CD0 – 1/2 rho V infinity cube S*k*CL square this is Cl square. From the second equation of climb we have L=w cos gamma alright so for the small angle of climb be can be closely assumed as L=w so the corresponding CL is 2 w/s/ rho V infinity square right. Substituting this in the above equation what we have is rate of climb=so what is this number.

This is CL3 right what was this equation and this you can state it as CL4. Consider this equation as CL4 rate of climb=so say this as CL4 and this as CL5. Okay consider this as CL4 and last equation as CL5. Now we have rate of climb=1/w times power available –1/2 rho V infinity cube S*CD0 – 1/2 rho V infinity cube S*CL square* 4w square/ rho square s square v infinity cube V infinity to the power of 4.

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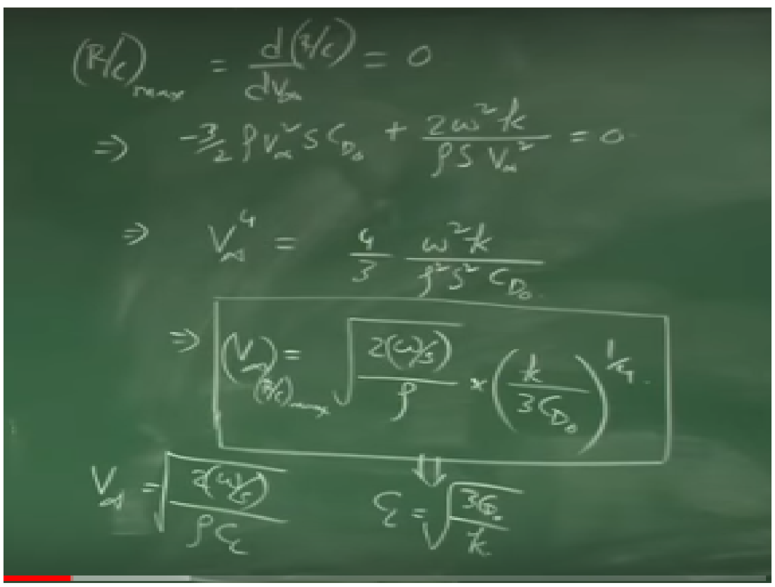

So, rate of climb if I need the maximum rate of climb for this rate of climb max I differentiate this rate of climb with V infinity and equate it to 0 for rate of climb maximum right. So, that implies -3/2 rho V infinity square S*CD0 and this will be-+ 2w square*k/rho*S*V infinity square=0 alright this implies V infinity to the power of 4=4/3 w square*k/rho square S square CD 0.

This implies V infinity is square root of 2w/s/rho right root over 2w S/rho*k/3CD0 raised to the power of 1/4. So, this is the velocity condition for the corresponding jet of plane maximum is the corresponding velocity condition. So, you remember this equation So what is in-general velocity during the flight with the climb that is influence. So, the corresponding velocity of flight will be twice the wing loading /rho*CL Corresponding CL of flight.

So, here can you see this CL is square root over 3 CD 0/k right. The corresponding CL for this particular case is CL= square root over CD 0 /k and this velocity is the minimum power requirement velocity so that is the reason why we mentioned power required is minimum right. So, if you fly at minimum power requirement for this particular quantity is less we have higher specific excess power from the given power plant.

That means if you are operating at the maximum power. You will have the corresponding maximum rate of climb so this condition corresponds to CL power 2/3 CD maximum right. When you do CL power 3/2 CD max the corresponding CL value is root over 3CD 0/k which is the minimum power requirement condition in a level flight. So, for the while both are same rate of climb maximum minimum power required.

So, while differentiating this equation this rate of climb with V infinity. What we assume this power available is constant with velocity right which means it is 0 affected with velocity but indeed it is 0 true. Unless you use very popular for different altitude it will 0 exactly remain constant. So, that is one assumption we have considered here and this power available is sharp power times the efficiency.

And moreover this efficiency factor that is also seems to be constant with. So, you know what is the corresponding velocity for rate of climb max right? Now let us say how you select a power plant based upon this. We have two parameters right now for in case of the small UAVs we have cruise and climb are the major phases of this flight right and you got to know what is the power requirement in cruise maximum power requirement.

At the same time, we should also get to know what will be the power requirement. Or what should be the power supplied to the system from the power plant for various climb rates right. So, if you can realize this equation if you can understand the power requirement then you can select ok what you pick up the maximum thing maximum power requirement of the total flight envelope and then correspondingly with an efficiency factor select the power plant right.

What you need to take as an input is this rate of climb for different rate of climbs rate of climbs.

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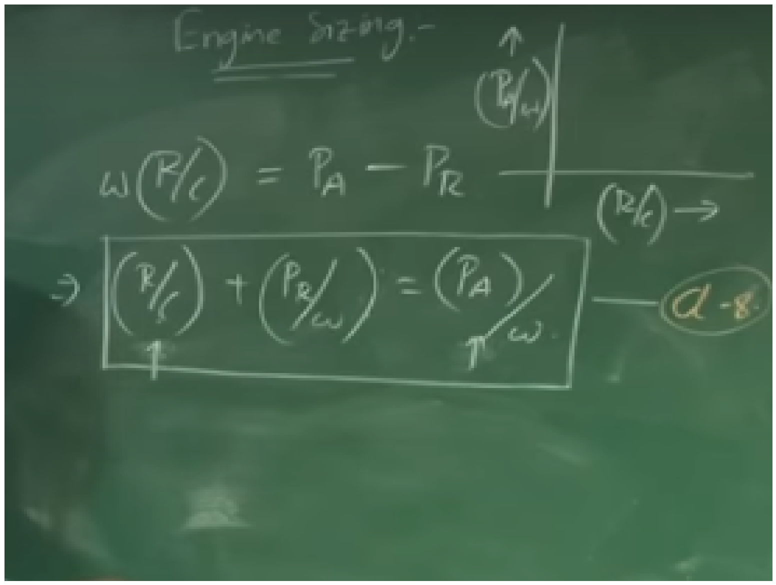

So, we have rate of climb*w = power available –power required alright so for different rate of climbs so consider rate of climb as an input. If I want to get a plot where this power available / load and the rate of climb for different rate of climbs it should be corresponding power available/weight ratio. What is the maximum rate of climb? you have to do, has to perform; so the corresponding power requirement you will select.

And based upon the power requirement you can select the corresponding engine right. So, how to calculate that and how to get that. So, consider the rate of climb desired rate of climb and plug-in to this plug-in that rate of climb into this equation which is CL5 and 6 so this is your CL 6 this is your CL 7 and this is your CL 8. So, the aim is to figure out what is the corresponding power required for different rate of climbs.

Or say what should be the output from this power plant for the different rate of climbs. So, you know from the mission requirements you can fix this rate of climb what should be the maximum rate of climb that you have required it has to perform. So, that maximum rate of climb you can figure out what could be the corresponding power available from the system because V infinity for this maximum rate of climb you can arrive from this equation.

And say if you want to plot the variation of power loading with the rate of climb what you need to do is plug-in the values of rate of climb. And find out what is the power required by W correspondingly plot the values and figure out. So, for the specific rate of climb what is the corresponding power available from the system with that number you can set up your power plant you can consider that number while selecting your power plant.

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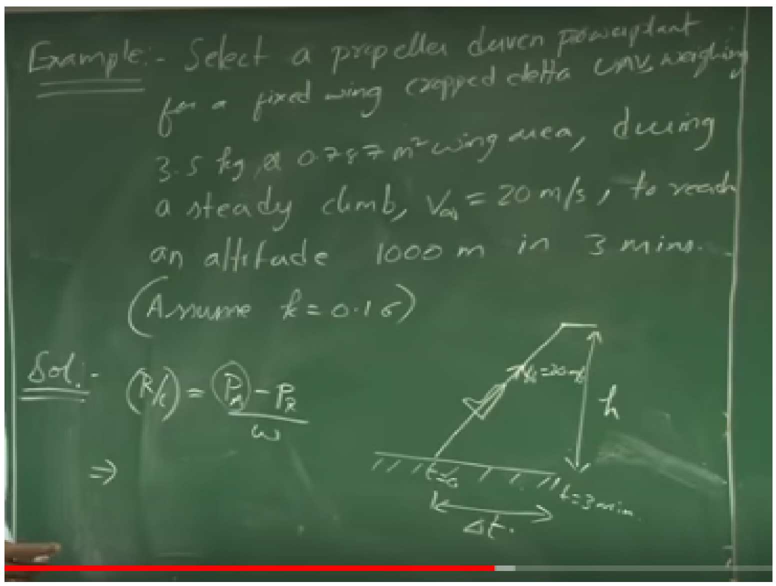

Now let us consider an example select the power plant with propeller driven power plant for a fixed wing cropped delta UAV weighs 35 kg and 0.787-meter square wing area during a steady climb. During the steady climb velocity of the climb is 20 meters per second during the steady climb to reach an altitude 1000 m in 3 minutes assure k=0.16. So, what we need to do we have to select the power plant for this configuration which has to perform a steady climb.

And the climb altitude should be 100 meters from sea level and 1000 meters from sea level and it has to reach this altitude within 3 minutes. Let us look at this solution we have to select the power plant for this particular mission profile particular phase of this mission. We need to understand what should be the power required by this system right. Total power required by the system during the climb.

So, that power should be delivered by the power plant. So, this is your desired altitude h you need to attain so this desired altitude h you need to be attained within delta T of 3 minutes consider delta t t=0 t= 3 minutes. So, from our equations and we know infinity = 20 meters per second velocity during this climb. So, we know rate of climb=power available–power required/ weight of this configuration.

So, I need to know what should be the power available from the power plant to perform this particular task. So, that I can select the corresponding power plant w*rate of climb right.

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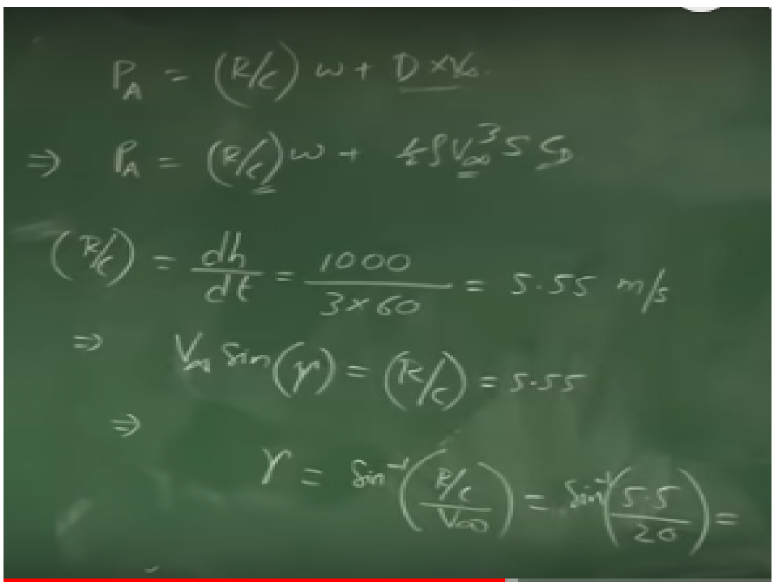

So, this power available=rate of climb*w+power required which is drag*velocity this is the power required in this case this drag*velocity. So, power available=rate of climb*w+1/2 rho v infinity cube S*Cd this = if we know what id CD here we know what is velocity of climb we should know what is the rate of climbing order to find out what is the corresponding power output from the power plant.

So, what is rate of climb is dh/dt which in this case is dh is 1 kilometer 1000 meters it is given here right you need to climb 1000 meters in 3 minutes. So, what we have is 1000/delta t is 3*60 this is meters per second which is approximately 5.55 meters per second. SO, from here can we estimate what is the climb angle. Since we know rate of climb is v infinity sin gamma=rate of climb right so this =5.55 meters per second.

This implies v infinity you know sin gamma =or gamma=sin inverse rate of climb/v infinity which is sin inverse 5.5/20 meters per second because the velocity during the study is 20 meters per second. So, this is approximately 16 degrees. So, the corresponding angle of climb is 16 degrees. Now we know what is the rate of climb angle of climb we need to calculate power requirement during this condition. So, w is drag*velocity right?

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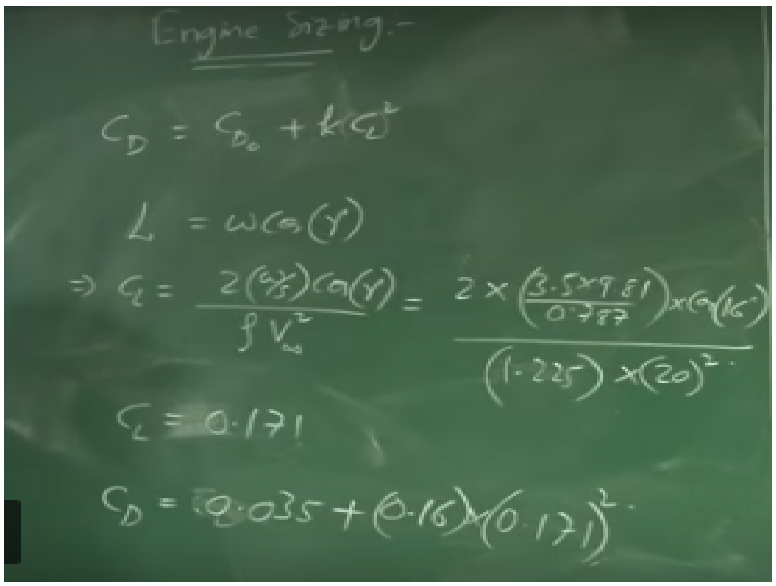

So, what is CD how do we get CD CD=CD0+k*CL square right so we need to know what is the corresponding CL for this flight condition right. So, we have another equation from climb 2 we have L=w cos gamma right. So, this implies CL=twice the wing loading/density*v infinity square*cos of gamma this implies this is 2*w/s w 3.5*9.81/0.787 so wing loading *cos of 16 degrees/1.225 it is an assumption that we are taking.

Density 1.225 is an assumption here that we have considered else you can otherwise take an average value which is the mean of density at 1 kilometer in sea level density. So. w*v infinity square what is v infinity square here it is 20 meters per second 20 square. So, what is CL value here CL=0.171 right if I am not wrong 0.171 right and yeah 0.171. Now you got the value of CL you know what is k you substitute the value of CL and k in this equation right.

So, CD0 should be given right in this equation let us take CD0=0.035 right you can refer to you previous example it is the same configuration what is CD? CD=0.035+0.16* CL square is 0.171 square this is to be.

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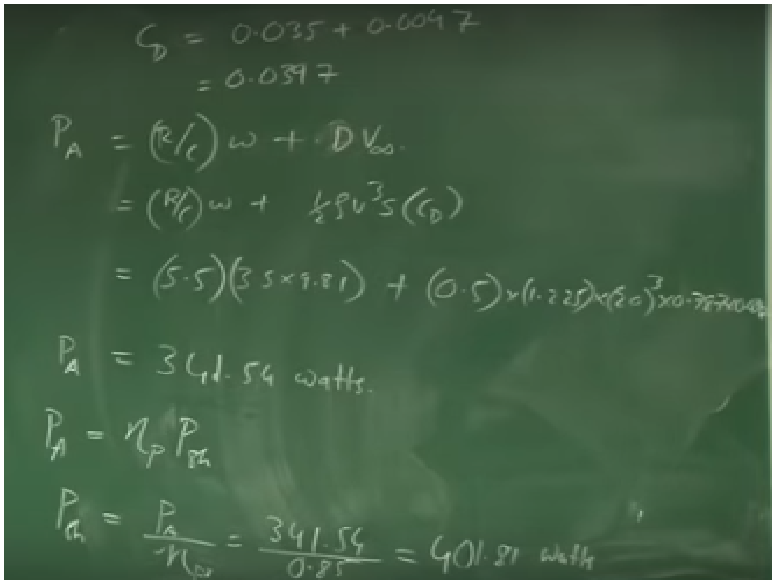

CD = 0.035 + 0.00047 = 0.0397 CD so now you have CD you can substitute in this equation. So, what we have power available= rate of climb * rate of this aircraft+power required which is drag*velocity right. So, this is rate of climb*w+1/2 rho v cube S*CD. So. what is rate of climb here 5.5 meters per second that is the vertical velocity*3.5*9.81+0.5*1.225*20 cube *0.787 what is the CD value 0.0397. So, the power available should be 341.54 watts.

So, this should be the power output from the power plant. Right, you should select a power plant it must deliver this much of useful power right. Now but we know power available is propeller efficiency*shaft power right so each engine is specified in terms of or the specifications of the engine are presented in terms of shaft power available shaft. So, this P shaft power =power available/efficiency of the propeller which is 341.54.

So, assuming the propeller efficiency of 0.85 consider it as p as 0.85 okay 0.85 what you can what you get from the shaft power 415 401.81 yes 401.81 watts. So. what do you think is the distance, horizontal distance covered during this climb right we can also estimate the horizontal distance here.

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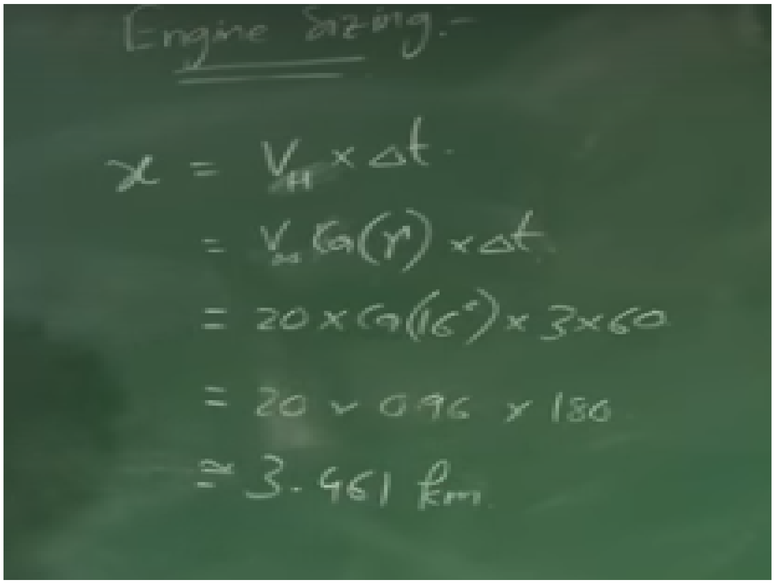

So, the horizontal distance travelled let us say x=since we are climbing with a constant velocity right v infinity* or component horizontal component of velocity*delta t. Since velocity is constant. So, what is the horizontal component of velocity climb velocity* cos component of this climb velocity right. Cos gamma*delta t=20 meters per second cos of 16 degrees*delta=3*60 degrees right =20 times 0.096 approximately*180.

This is approximately 3.4 kilometers 460. So, this is approximately 3.461 kilometers this is a horizontal distance travelled during this climb.

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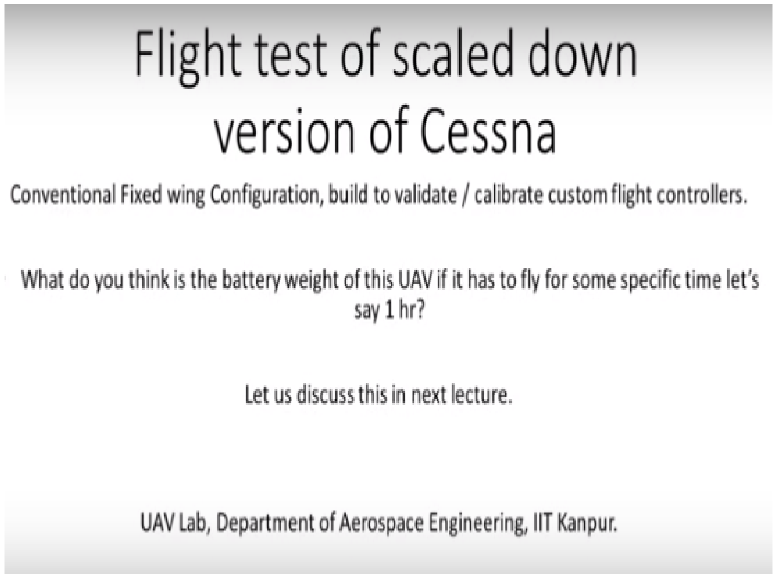

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