Design of Fixed Wing Unmanned Aerial Vehicles
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Lecture – 12
Calculation of Performance Parameters and Selection of Power Plant

Dear friends, welcome back. In our previous lecture, we discussed about how to estimate the power required for various cases as well as the thrust required and we figured out what is the minimum power required and minimum thrust requirement of the system as well as the maximum velocity that at which you can fly with a given power plant and we also witnessed about what is a stable region of flight and what is unstable region of flight.

So, what is the whole idea behind doing the behind this exercise. Otherwise say how can you select a power plant for a given UAV right. So as mentioned earlier we need to figure out what is the corresponding requirement of the system during various phases of flight. Now since we discussed about level flight which is the crew is here to study level flight. Let us figure out a power plant of a UAV by taking an example.

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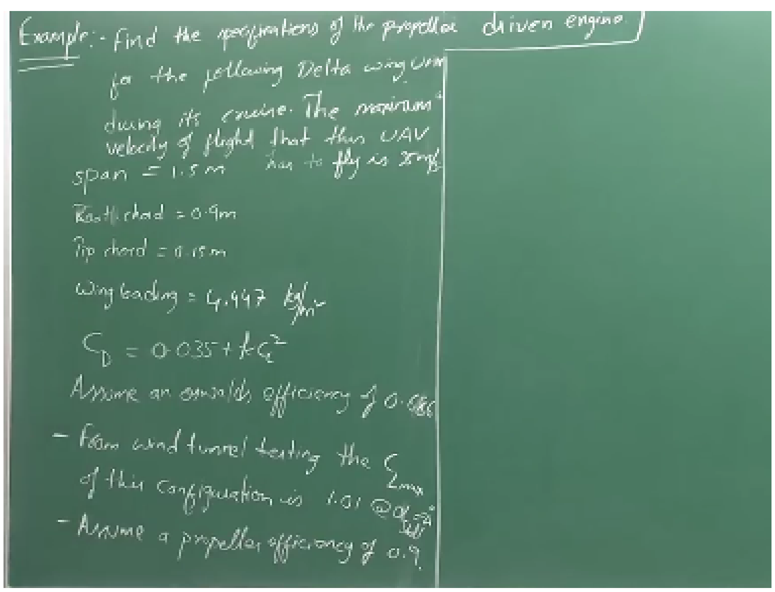

Find the specifications of the power plant for the following delta wing using UAV during its cruise say the span of the UAV 1.5 meters and the root chord is 0.9 meters and the tip chord is 15 centimeters. Let us say wing loading 4.447 kg per meter square and the drag polar of this UAV is

0.0.35+KCL square. Assume Oswalds efficiency is 0.666metres 0.686. So, the maximum velocity at which the maximum velocity of flight.

That, this UAV has to fly is 35 meters per second from wind tunnel testing the CL max of this configuration is 1.01 at 20 approximately alpha stall 21 degrees and you can also assume a propeller efficiency of 0.9 right. So, find the specifications of propeller driven engine for the following delta win UAV during its cruise. The Maximum velocity of flight that is expected from this UAV is 35 meters per second. Now given the span of the system the span of the wing.

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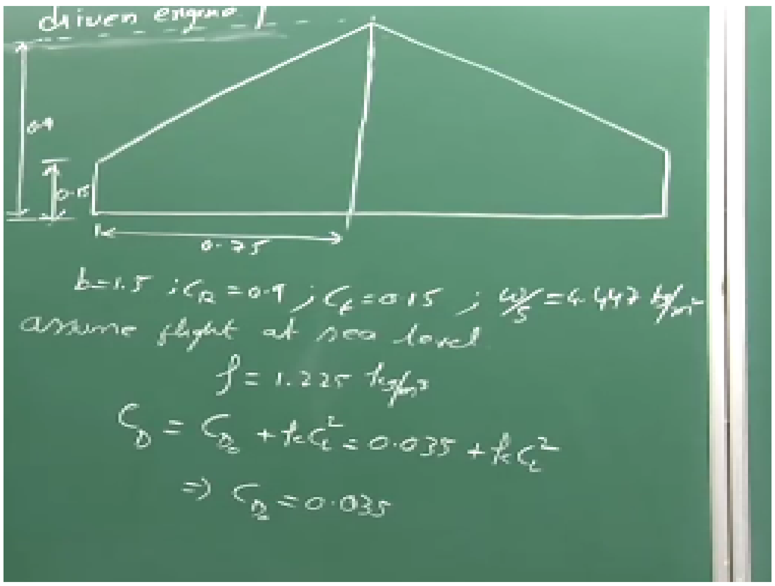

Let us say this delta wing UAV it has 1.5 meter's span and the root chord of 0.9 meters and the tip chord of 0.15 meters 1.5, this is 0.9, this is 0.75 right and the Oswald's efficiency factor. So b is 1.5 CR is 0.9 CT in this case is 0.15. And wing loading is given w/s right w/s is 4.446 447 kg per meter cube meter square sorry, kg per meter square. And we assume that this aircraft this UAV has to perform its flight at sea level right.

So we can assume flight at sea level so density at sea level is 1.225 kg per meter cube and the track polar is given for this given UAV which is CD0+KCL square=0.035+K*CL square this is =CD0. The propeller coefficient is 0.035 and we need to find out what is K induced a correction factor. Now we need to understand like what should be the power plant specifications. That means, so one of the mission requirement is that the maximum velocity is 35 meters per second.

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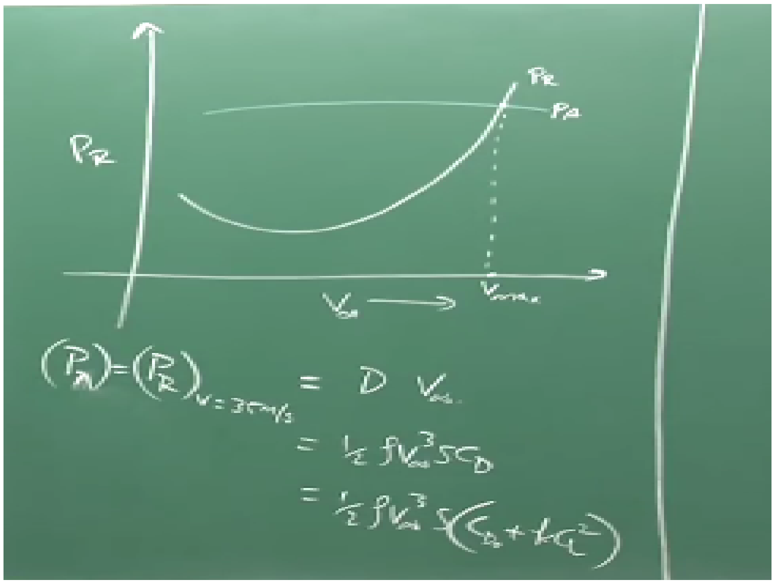

So, we know that from our previous lecture we can refer to our previous lecture and say so this is the power required and this is your velocity. So, this this has a typical variation this curve represent typical variation power required velocity and say if this is your power available which almost remains constant with velocity for a propeller driven aircraft. So, this is power available and power required.

So, we need to mention what is the maximum power required by the or by required by system right . So, if you know the maximum power required by the system then we can say that this amount of power has to be delivered by the power plant propeller as well as engine combination right. So, if you come up with these specifications like what is the power available. We will be able to specify the corresponding power plant right.

So, say this is your v max which in our case is 35 meters per second. So, you need to find out this power this point of intersection so for this power required if power available at that point is = power available max so because this is your maximum velocity right. So, this much this should be your power available maximum or say that may not be necessary. But you can take a factor of safety and you can use it that may not be the maximum capability of the engine itself.

But this should be required power that need to be delivered by the power plant. To the system to achieve the level flight at this required velocity right. So, the maximum velocity we require is 35meter per second. So power required at v=35 meters per second and this equals to drag*velocity which is 35 meters per second in this case. So ½ rho infinity cube s*CD, so this =1/2 rho v infinity cube s*Cd0+KCL square.

Now what are unknowns here s is unknown s, we need to find out k. We need to find out alright and CL for this velocity right okay.

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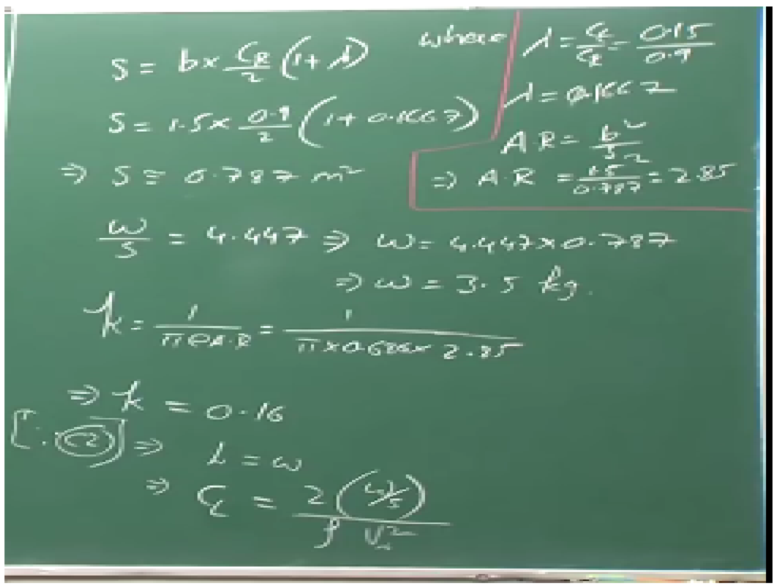

How to find that so s=b*CR+CT/2 which is CR/2 1+lamba so what is lambda where lambda=CT/CR which is 0.15/0.9 lambda=1.667 0.167 0.1667 not 0.167 right. So this is your lambda we substitute lambda here. And we know what is CR is given as an input here 0.9 meters and b is 1.5 meters so 1.5 times 0.9/2+1+.1667= this implies s = approximately 0.787-meter square okay, we got to know what is the area here right.

And if you want to find out what is the weight of this UAV. Wing loading is given w/s=4.447 kg per meter square this implies w=4.447* what is s 0.787 this implies w is approximately 3.5 kgs right . So, the weight of this UAV is approximately 3.5 kg now you have area and you know density what is k k for this UAV is 1/pi eAR so what is K pi * so the Oswald's efficiency is given here which is 0.666 it is 0.686.

So, the Oswald's efficiency is given as 0.686 for this configuration and what is the aspect ratio aspect ratio= b square/s right that implies b is 1.5-meter square/0.787=2.85. So, substitute that aspect ratio here 2.85 k is approximately 0.16 right. Now we have k here now we need to find out what is the corresponding Cl how do you find Cl? we have from equation c2 since it is a level flight right, we are talking about level flight.

During level flight thrust = drag of the system lift = weight of the system since c2 L=w which is CL= twice the wing loading /rho*corresponding velocities. So, if you want to fly at the maximum velocity or the maximum velocity that is the UAV has to perform is has to fly has to fly is it 35 meters per second. So, substitute 35 meters per second here and you have the corresponding wing loading data and you know what is density of flight.

Right the altitude of flight where you can find the corresponding density and you can figure out what is the corresponding CL for this configuration CL for this particular flight.

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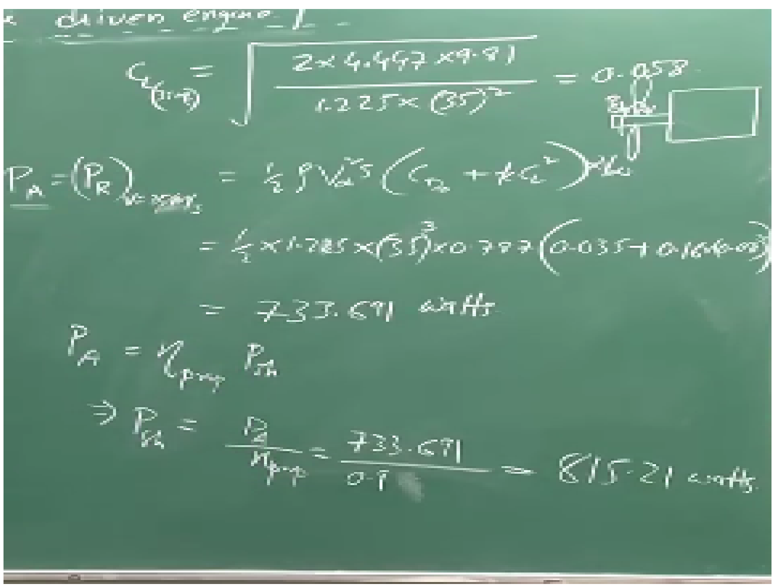

So, CL for this particular velocity 35 meters per second=square root of 2 times w/s is 4.4447 kg per meter square right. So but w is it should be in neutral right its force. So, convert this to Newton per meter square/1.225 is the density since we are flying at sea level and what is corresponding velocity is 35 meter square meter per second square =0.058 see the CL required for this particular flight is 0.058 which is very less right.

What you have to find out is power available=power required at v=35 meters per second 35 meters per second which is =1/2 rho v infinity square s*CD0+k CL square this =1/2*1.225 1.225*35*v infinity this becomes 35 cube*0.787*CD0 is 0.035+0.16*CL square 0.058 square this=733.691 watts this is the power that that is required by the system. The system demands the UAV demands power of 7 734 watts.

When you are flying at a velocity of 35 meters per second during cruise. So, this is the power available right but what we get as an output is a shaft power from the engine. So the engine is rated in terms of shaft power right ps psh is a shaft power right. So, when the shaft is combined with the propeller you will get the corresponding useful power right. So, propeller efficiency is given as 0.9 and we know power available = efficiency times shaft power.

So, what should be the corresponding shaft power that the engine has to deliver. This power available/eta propeller efficiency which is 733.691 watts/0.9 it is the propeller efficiency that is given* yeah 0.9 815.21 watts. So, you have to select a power plant which gives at least 815.21 watts if you are if you want to move it 35 meters specific. But ideally this should not be at the peak power of the IC engine or the whatever the power plant that you select.

It should be so you need to get this peak power at a 50% of what it is rated for say if your power plant peak power is rated about 1200 or so then this will be about 60% of it or 70% So, that should be a good number to select right. So, you need to select a power plant which delivers this power at 60 or 50 to 60% of its rated power.

So, this now let us extend this question a bit. So, you have figured out what is the shaft power right now how do you get to know like what can be the minimum velocity that I can fly at the same time what can be the corresponding minimum power that I can that the system requires right.

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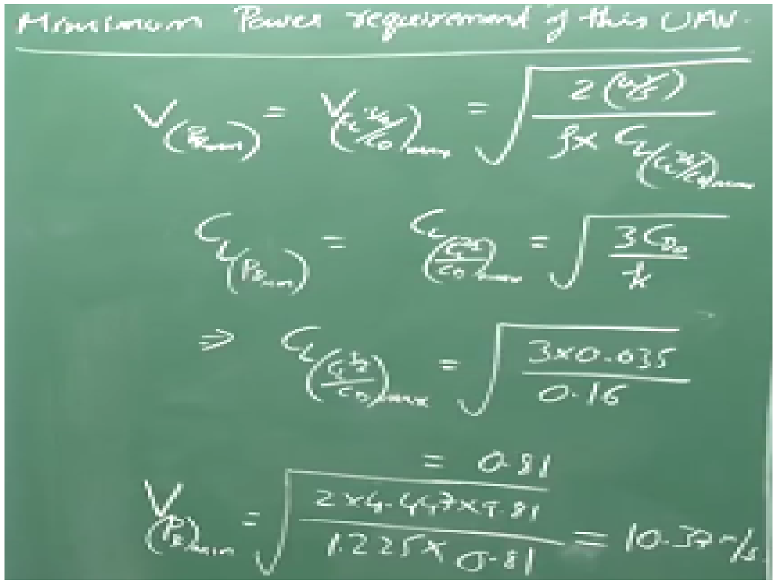

Minimum power requirement of the system of this UAV how do you get this you know to find first what should be the velocity right. So, you know what is the range of velocity that you can fly do you know it or not what should be the range of velocities either velocity for minimum power required or stall velocity right and the upper limit this maximum velocity that you want. So let us find out the lower limit of the velocity range.

So, for that we need to find out 2 velocity the stall velocity as well as yeah the both the stall velocity or the velocity for the minimum power required. Now let us see what is the velocity for minimum power required power required minimum power required which you can attain by velocity for CL power 3/2/CD maximum right which is = square root of 2 twice the wing loading/density*CL for power required minimum which is Cl power 3/2 /CD maximum right.

This equation we got it from C2 L=w right lift = weight in this case since it is a cruise. So, what is the corresponding velocity for power required minimum. So, to get this we need to know what is CL for minimum power requirement condition which is CL for CL power 3/2/CD maximum alright. So, what is that condition CL power required minimum=Cl for CL power 3/2 /CD maximum which is=square root of 3 CD0/k so this implies CL.

For CL power 3/2/CD maximum=square root 3* what is CD0 0.035 which we obtained it from drag polar and K we have calculated which is 0.16. So this turns out to be 0.81 see the Cl almost demands see the maximum Cl we have it is about 1.01 right so we need to fly almost close to stall angle of it. So, as the velocity decreases the corresponding requirement of CL increases right we need to trim at higher angles of it.

Now substitute this value here twice wing loading what is the what is wing loading 4.447*9.81 because 4.447 is given in kg per meter square we need to convert that to Newton per meter square density is 1.225 sea level density kg per meter cube and the corresponding CL for this condition is 0.81. So this turns out to be approximately 10.37 meter per second all right. So this is the velocity at which you need to fly.

If you want to maintain a minimum power requirement condition but is this velocity possible we had to check if it is < the stall velocity, then you will not be able to fly right you will not be able to fly in a level flight condition.

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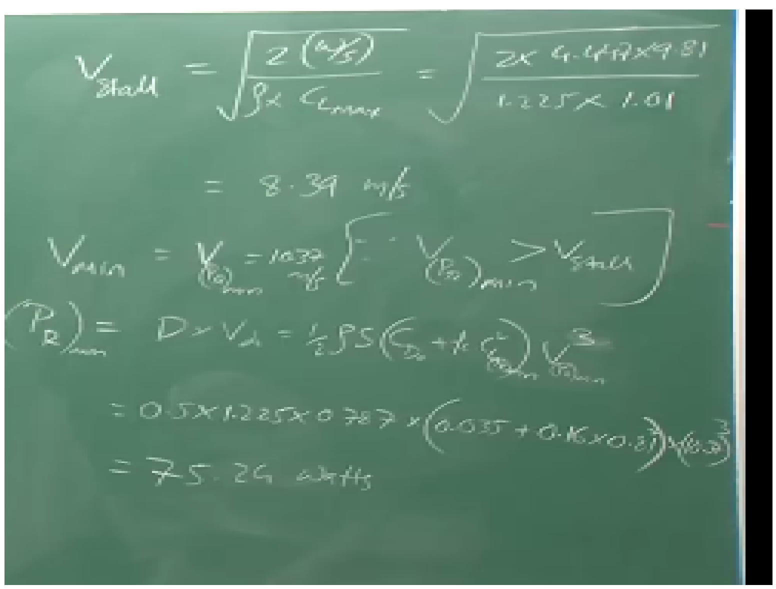

Now we need to find out what is the stall velocity s well V minimum is obtained later . So, stall velocity is square root of twice w/s/rho*CL max. So, CL max is twice w/s is 4.447*9.85*1.225*CL max is 1.01 8.39 meters per second. So V minimum =V stall since V for power required no V minimum = V for minimum power requirement power required minimum =10.37 meters per second.

Why because power required minimum is >v stall that means so v stall falls in the region of unstable flight right region of velocity region of unstable flight. So, that is why we need to we have to fly at v for minimum power required. So, we can straight forward say that right because the CL for this condition is 0.81 but CL max is 0. 1.01 that means CL for minimum power requirement is <CL max.

That means in the denominator this quantity is < the other quantity which means the velocity will be higher. So, we can straight away say that we can fly at minimum power required so we have estimated the minimum power minimum velocity of flight and what should be the corresponding power? power required by the system so power required by the system = power required minimum right.

This is the velocity for minimum power required= drag times velocity which is 1/2 rho s CD0+KCL square*velocity for power required minimum and CL per square power required minimum sorry, it is cube please correct this is cube because 12 rho square and v infinity it is cube. So, CD0+KCL square CL for power requirement minimum condition. So, 0.5*1.225*0.787 *0.035 + 0.16 *0.81 square. So, this is your CL for minimum power requirement condition.

So, you need to substitute this value here so you need to substitute this value substitute this value this equation 0.81 square times and the corresponding velocity for minimum power requirement is 10.37 right. This is the corresponding velocity for minimum power requirement 10.37 cube = 75.24 watts see for maximum velocity you need around 734 watts. And for minimum velocity condition you require 75 watts.

Now let us look at another example the same question let us solve for a jet engine find the specifications of the jet engine for the following delta wing UAV during its cruise the maximum velocity of the flight that this UAV has to fly is 35 meter per second. Right so again here so similar to the propeller wing aircraft we need to find out in this case the jet engine is rated in terms of thrust right.

In propeller wing air craft, it is rated in terms of power. So, we need to find out what is the maximum thrust requirement or say here since the maximum thrust requirement comes when you fly at the maximum velocity. For this case the maximum velocity that is required as per the mission is 35 meter per second. So we need to find out the corresponding thrust required at 35 meter per second. When the jet engine need to deliver the thrust at 35 meters per second to this particular flight condition

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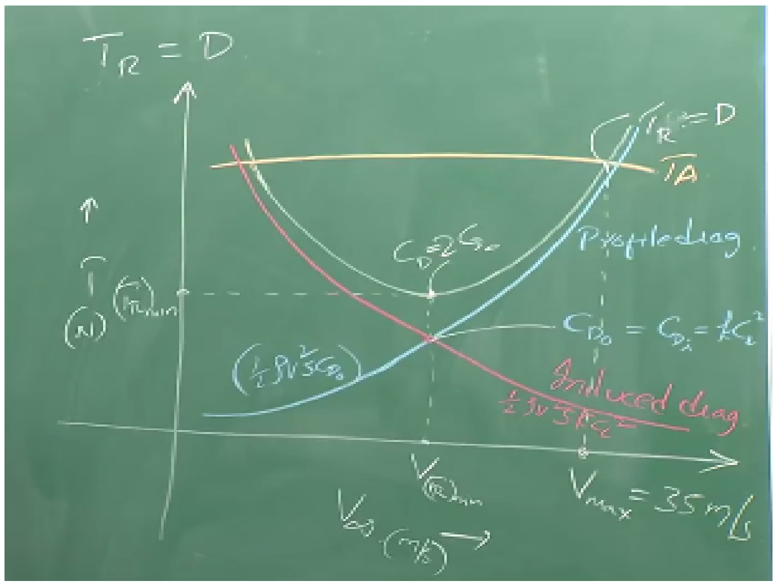

Let us see how to proceed this problem so what we have from c1 for level flight thrust required = drag. If you look at thrust versus velocity variation of thrust and velocity is newton or kilo newton and this one is meter per second. Now the typical plot of thrust required velocity this one thrust required is nothing but drag here. So, this is thrust required I said this is your thrust available from the engine right.

Now, what is this plot thrust required in velocity it is the summation of which is nothing but drag in this case right for a level flight case this thrust required is drag which is the summation of profile drag and induced drag right. So, induced drag will be lower or at higher velocities right. So, as the velocity increases this is profile drag so as the velocity increases the profile drag increases and the induced drag decreases this is induced drag curve right.

So, this intersection where CDI CD0 = CDi. So this is like 1/2 rho v square is CD0 right and this is 1/2 rho v square s*KCL square KCL square we can term it as CDi co-efficient of induced drag. So, at this point these two co-efficient are equal so at this point corresponds to CD0 = CDi =K*CL square right. So, KCL square =CD0 so the total drag co-efficient at this point the total drag co-efficient at this point is 2CD0 = CD=2CD0 at this particular point.

So, this is the condition for when this is achieved when your intersection when you were flying with L/D maximum. So, the corresponding velocity is velocity for TR minimum or L/D maximum. So this point corresponds to thrust required minimum right yeah and when do you achieve maximum velocity? So when thrust required=drag right thrust required = thrust available from the power plant.

So, this particular velocity will be the maximum velocity of flight and for this particular cruise it is 35 meter per second. So, if this is the case what should be your thrust requirement that is the problem we need to solve right.

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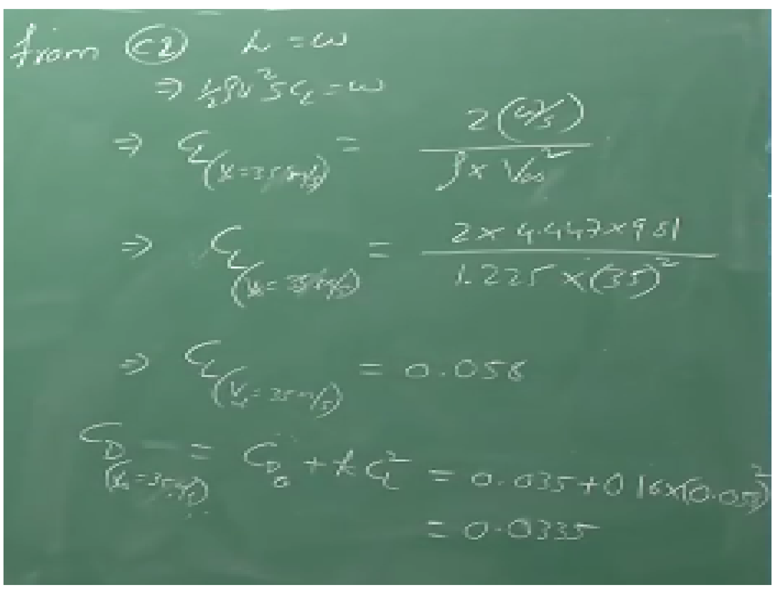

So, what we have is from c2 from c1 what we have is thrust = drag and you know thrust required = w/L/D which has called by w/CL/CD for maximum TR max or TR at velocity 40 35 meter per second = w/CL for 35 meters per second or CL/CD for 35 meter per second with velocity 35 meter per second. So, what is the weight of the system we have earlier calculated so the wing load here is 4.447 kg per meter square and area we have figured out as = 0.787 meter square.

And aspect ratio is 2.85 and Oswalds efficiency is given as 0.686. So the corresponding induced corresponding factor is 0.16 and from the drag polar we have CD0 =0.035 drag polar CD0=right. So, what will be the CL for 35 meter per second from c1c2 we have L=w which is 1/2 rho v square CL=we have CL for this particular case when v infinity is 35 meters per second, 35 meter per second = twice the wing loading /density at the respective altitude*the corresponding velocity of flight which is in this case is 35 meters per second.

This implies CL versus velocity which is considered the maximum velocity for this UAV 35 meters per second as per the mission requirements 35 meters per second is the maximum velocity this is twice the wing loading which is 4.447*9.81 will convert this to Newton per Meter square/1.225 kg per meter cube*35meters per second square. Corresponding CL for V infinity 35 meter per second is 0.058.

So, this is not going to change right we have earlier calculated this is not going to change either the jet engine or the propeller driven engine that is not going to change any CL requirement because you are flying a cruise. The propulsion system whatever the way it is I mean ultimately we need thrust right. Whether it is generated by electric driven engine or a propeller driven engine or a jet engine what you have a CL here which is 0.058.

Now using this CL, we can calculate what is CD for this case is at v infinity is 35 meters per second =CD0+KCL square it should also remain the same What is the value 0.035+ what is K 0.16*CL square which is 0.058. So,0.0355 which we have earlier derived right this this is exactly same CD at v infity35 meter per second. Please make a correction it is 0.0355. So what is L/D of this configuration at this particular flight condition. What is the L/D at that particular flight condition?

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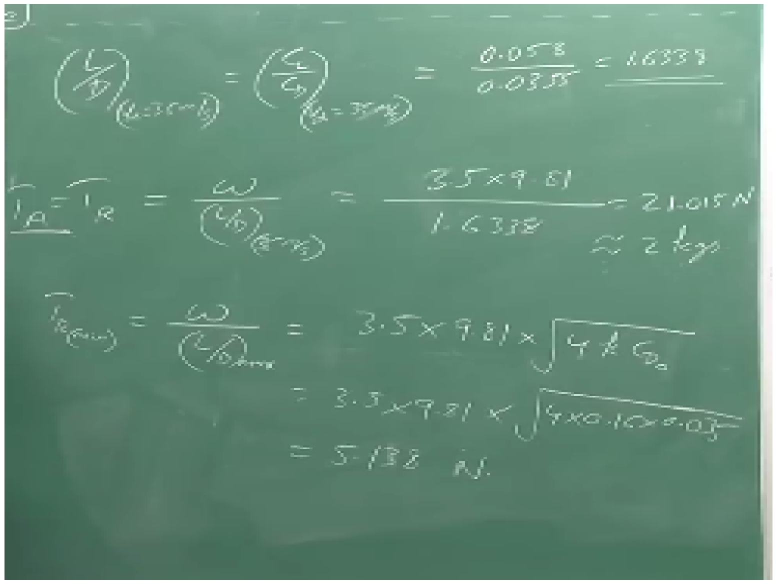

L/D at v infinity 35 meters per second=CL/CD at v infinity 35 meters per second which is =CL at 35 meters per second and CD at 35 meters per second which is 0.058/0.035=1.6338 reason why it is by default delta wings is very less right in other cases it would have been at least 16 14 in delta wings it is like 1.6 because the profile drag is very high for this delta wings. The thrust required.

So, this should be the thrust required available which is =W/L/D at 35 meters per second. This W is 3.5 kg *9.81/1.6338 21.015 Newtons which is approximately 2 kgs of thrust. You need to give 2 kgs of thrust to lift a UAV of 3.5 kg if you want to move it 35meters per second with this particular drag polar. So, this should be the amount of thrust that this engine has to develop. Now what should be the minimum thrust requirement.

Thrust required minimum=w/L/D maximum. So, this should be the minimum amount of thrust you need to supply in order to have achieve a level flight for this particular UAV right. 3.5*9.81* what is L/D max root over 4K CD0 3.5*9.81* square root 4*0.16*0.035 5.138. So, you need to fly at 5.138 newtons which is approximately 0.5 KG right that is 500 grams. You need to supply 500 grams of thrust if you are flying at L/D maximum.

What is L/D max here? Now let us look at what is L/D max for this case what is L/D max that is CL/CD max which is 1/root over 4K CD0 that is 1/root over 4*0.16*0.035. So, this value is

6.681. So, L/D max for this configuration is 6.618 whereas the L/D in this particular case is 1.6 approximately 1.6 right 1.64 Cl for L/D max root over CD0/K which is root over 0.035/0.16 which is 0.4677 right this is the CL for this particular case.

And the CL for you are flying it minimum velocity minimum thrust requirement is like minimum velocity for this flight. Why because the corresponding velocity of flight we have not calculated let us look at that then we can comment it again. So, the CL for L/D max is 0.4677 right and what is CD CD0+KCL square so which is 2CD0 it is like twice 0.035 it is 0.7 0.07 right this is the value of drag co efficient at this particular flight.

So, how to achieve this you need to trim at the corresponding angle of attack. Now what is the velocity for this thrust required minimum condition =square root of twice w/s this is from C 2 using C2 equations you can find it of . Since lift = weight 2W/rho 2w/ s / rho* corresponding Cl for L/D max twice what is the wing loading here 4.447*9.81/1.225* what is CL for L/D max is 0.4677 12.340 meter per second 12.34 12 meters per second approximately.

So, you need to fly at 12 meters per second the CL here is CL for L/D max is 0.467 alright whereas CL max is 1.01. So, since this is < CL max the stall velocity is < v12 because this is denominator right. So, you will have this velocity will be higher than the stall velocity and we have also e also calculate the stall velocity as 8.2 meters per second alright in our earlier in the earlier example we solved for stall velocity that is not going to change.

Whether you are using a jet engine or propeller engine right. So, the velocity for a minimum thrust requirement is 12.34. so this is your boundary for stable flight right velocity resume for stable flight right, this is the minimum limit the maximum limit that you already specified as per the mission requirement, so it is just 35 meters per second. So, you have a velocity range of 12 to 35 meters per second using this jet aircraft.

Right so see as the velocity decreased the CL value, the corresponding CL value has increased here right. Here the CL value is very less but the velocity is high, so the profile drag is higher. That is why the L/D is lesser. Let us look at another example.

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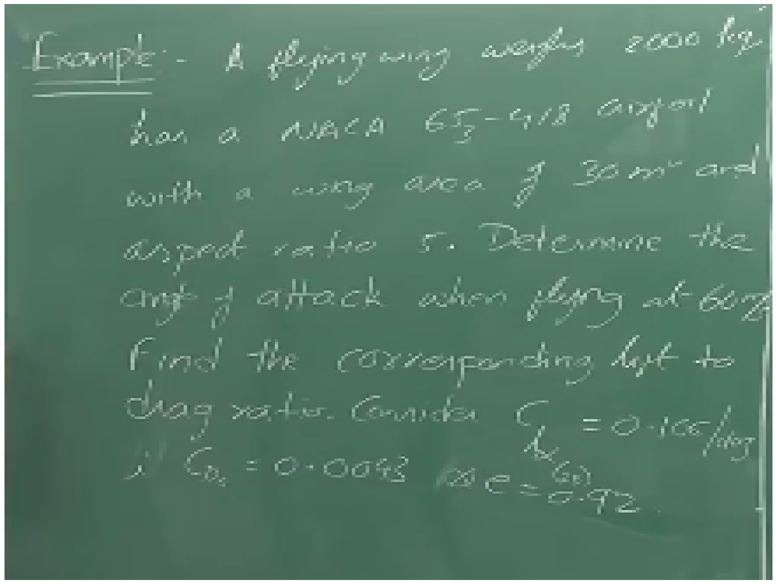

A flying wing weighs 2000kg has a NACA 653-418 air foil with a wing area of 30 meter square and aspect ratio 5 determine the angle of attack when flying at 60 meters per second when flying at 60 meters per second . Find the corresponding L by lift to drag ratio consider CL alpha of air foil 2D CL alpha 2D are for the air foil is 0.106 per degree and CD0 s 0.001043 and, CD0 and e is 0.96. So, consider e as 0.92 okay. 96 is too high.

So, this is the data that is given so there is flying wing UAV which weighs about 2000kg, and it is flying at a velocity of 60 meters per second at sea level assume it as flying it at sea level. So, it has an aspect ratio of wing area of 30 meter square and an aspect ratio of 5. So, we need to determine the corresponding angle of attack of flight. At the same time what is the L/D of this flight. The other data that is given is we have CL alpha 2D as 0.16 and CD0 is 0.043 and e as 0.92. right. So, how do we determine trim angle of attack?

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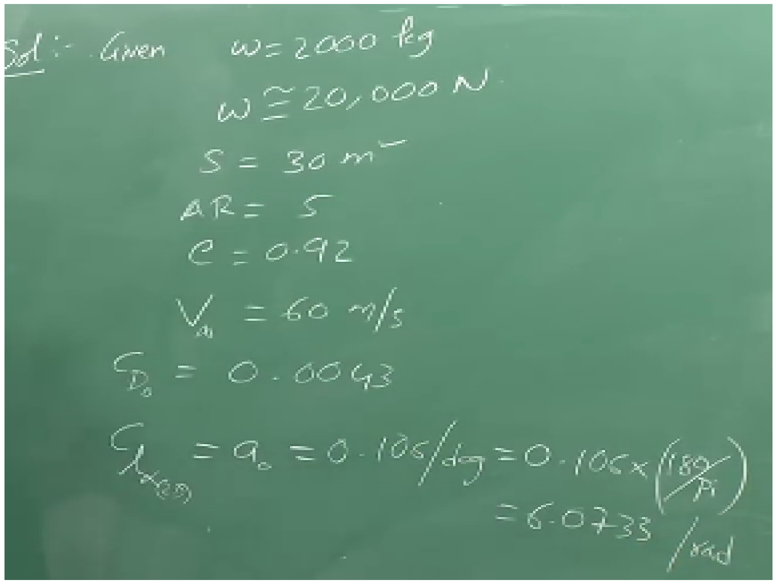

First, we need to know what is the corresponding C solution? First given w=2000kgs which is approximately =20000 newton right w*approximately by 10 right 9.81 and s is given as 30 meter square and AR is given as 5 and e is 0.92 and velocity who is velocity V infinity=60 meters per second right at the same time the CD0 of the wing is given as 0.0043 and CL alpha of wing. CL alpha of air foil that is 2D which is let us say a0 air foil CL alpha which is=0.106 per degree right.

We can convert into radiance 0.106*180/pi 6.073 6.033 per radiant. This is the CL alpha of 2D that is the CL alpha of the air foil. Now how to find out CL alpha trim for this particular case that means when you are flying at 60 meters per second how do you get the alpha trim of the UAV.

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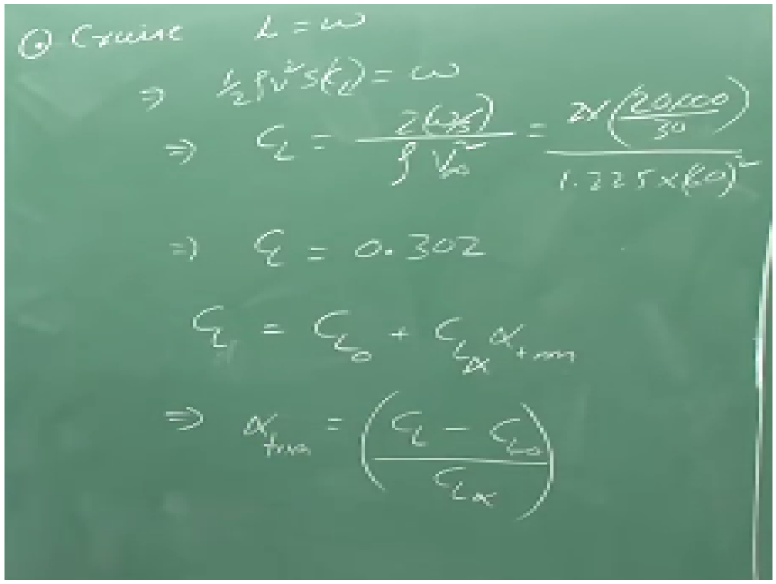

During cruise, we have from C2 lift=weight that is it should be 1/2 rho v square s CL=weight right. So, this should be your CL during cruise that is 2w/s/ so what is this w is 20000 newton/s is 30 meters square/1.225*60 square that is 6000.302. 0.302 is your CL for this corresponding flight right. So, assuming a linear range of angle of attack the CL design or CL for this particular flight condition=CL0+CL alpha of wing*alpha trim.

So, how to attain this is like alpha trim=CL for this current condition/-CL0/CL alpha of 3D. Now what we need to find is CL alpha and CL0 of the wing right. If you know what is CL alpha of the wing and CL0 of the wing we will be able to find out the corresponding trim angle of attack. Now how to find the CL alpha of the wing? We have the relationship right we derived it earlier

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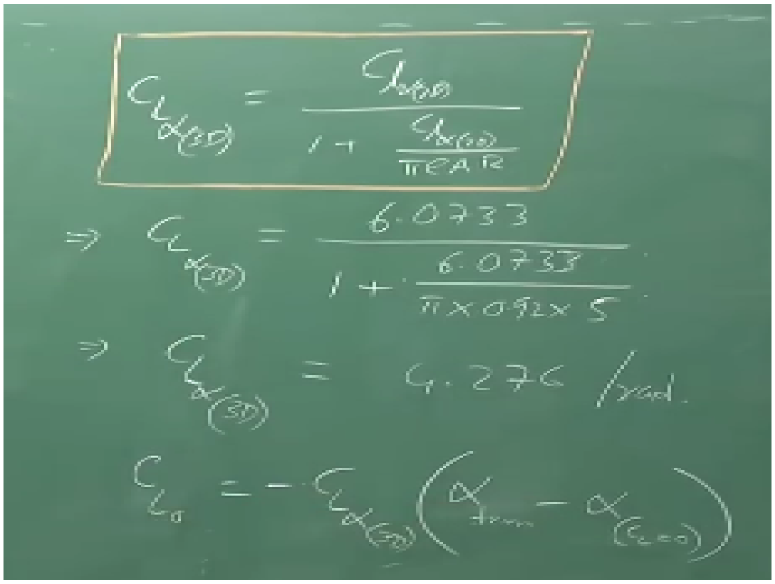

CL alpha 3D or for wing =CL alpha 2D/1+CL alpha/pi eAR. This implies CL alpha 3D=what is CL alpha 2D in this case? 6.0733/1+this is your CL alpha 3D per radiant. 2D of NACA 653-418 6.0733 /pi e 0.92*aspect ratio of 5 CL alpha 3D=4.276 per radiant. So, this is a corresponding lift curve slope of wing. We need to find CL0 of the wing how can we find -CL alpha 3D*alpha trim-alpha at which CL is 0 which will be same for both the cases.

Since we do not have the information about alpha at which CL=0 we can consider this entire angle of attack as angle of attack with respect to 0 lift line. So, we got CL alpha from here we know alpha trim if we want to find out the corresponding angel of attack of trim to achieve this CL what we need is CL0 since we got CL alpha from here. So, how to find CL not of this wing is -CL alpha *alpha at which CL=0.

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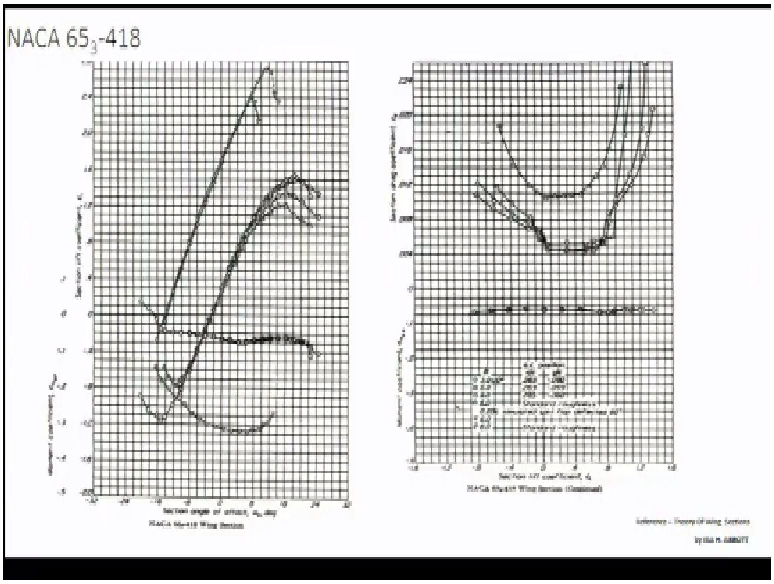

For 653- 418 from our previous lectures, you can refer those previous lectures the alpha at CL =0 for air foil is -2 degrees approximately -2 degrees.

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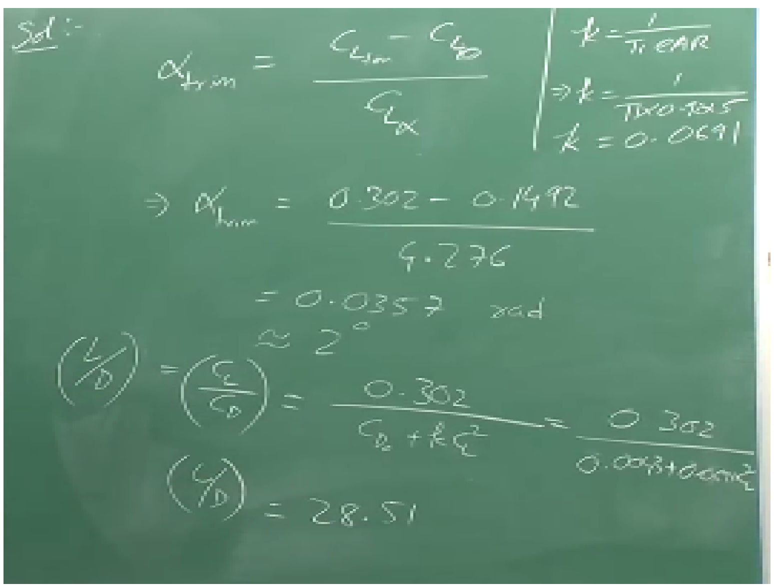

So, since alpha at CL0 remains same for it is an assumption that we consider it remains same for both air foil and wing. So, that -2 degrees here what we have is -4.276*-2*pi/18 0.1492. So, CL0 is 0.1492 so now the corresponding alpha to trim alpha trim=from this equation which is CL-CL trim-CL0 CL0/CL alpha=alpha trim=CL is 0.32, 0.302 - 0.1492/CL alpha is 4.276=0.0357 radiance which is approximately 2 degrees.

Right this is the angle of attack at which you need to trim this with UAV at 2000 kg UAV if you are flying at 60 meters per second with this particular drag polar. Now if you want to find out L/D for this particular flight condition you have CL and CD for this particular flight condition which is CL is 0.302 where CD is CD0+KCL square k you can find out you have aspect ratio and air foils efficiency.

What is k? k is a/pi eAR that implies 1/pi*0.92* aspect ratio of 5 0.0691 is the value of k. So. substitute that value of k here 0.302/CD0 is 0.0043+k is 0.0691*0.3 CL trim square. This = 28.51 right. So, L/D for this particular flight condition is 28.51. So, this UAV is flying at an L/D of 28.51 although it is a low aspect of string still the profile drag is very less for this.