Design of Fixed Wing Unmanned Aerial Vehicles
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Lecture - 17
Wing Planform Selection and Sizing and Flight Test of Cropped Delta Wing UAVs

Dear friends, welcome back. Yesterday we discussed about weight estimation by iterative process for electric powered propeller in an aircraft. At the same time, we started discussing about how to perform wing sizing.

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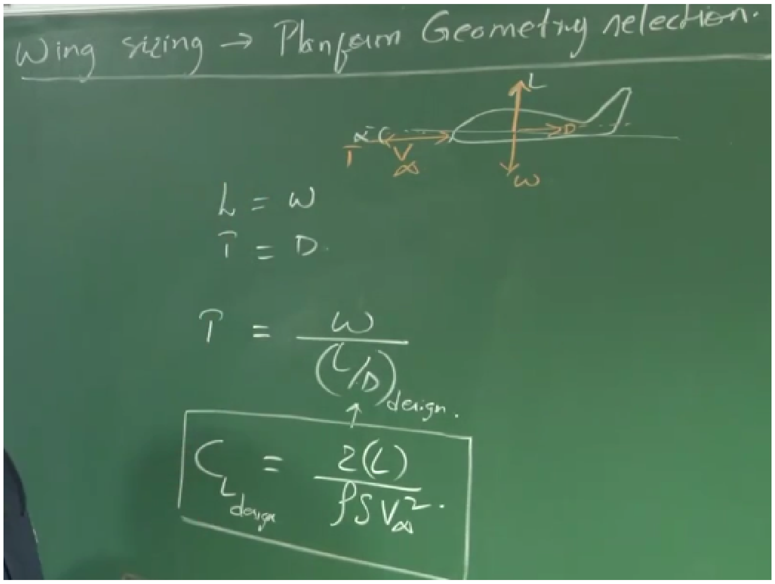

So let us talk about the wing sizing in terms of planform geometry selection. So we want this UAV, which is of a particular weight to fly at a particular velocity. The whole idea during cruise is lift should be equal to weight and the thrust acting in this direction, should be equal to drive, right. So while calculating the thrust required, we assume, it depends upon L/D W/L/D. So if you know this information at what L/D you are going to fly, you will be able to figure out what is the corresponding thrust required.

So when doing so you also decide what is the lift at the particular during that particular phase of flight, right. That means when you say lift, so you can also express the same as a non-dimensional parameter Cl, which is 2*L/rho S*V infinity square, right. That means, for this particular L/D there is a particular, see this is your design L/D, there is a design Cl. So design Cl is considered as an input while performing this wing sizing.

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So we need to design, say this is my wing, we need to design this wing to perform this particular cruise, which is the major part of the mission, right. So during cruise, by the way the weight of this wing is approximately 1.5 meters sorry 150 gms and what is the span? Span if you can see almost 1 meter span. 1-meter span wing with a carbon fiber tube attached to it. The whole set weighs around 150 gms and see it is a rectangular wing, you can see. It is a rectangular planform, right.

So, what is the chord of this wing? You can notice it is a symmetrical wing with a symmetric cross section of the profile. The chord is approximately 23 cm, ok fine. How much weight or say the lift generated by this wing or this planform, what is weight that it can sustain? Let us look into that. Let us try to see whether can we get the answer from this approach or not.

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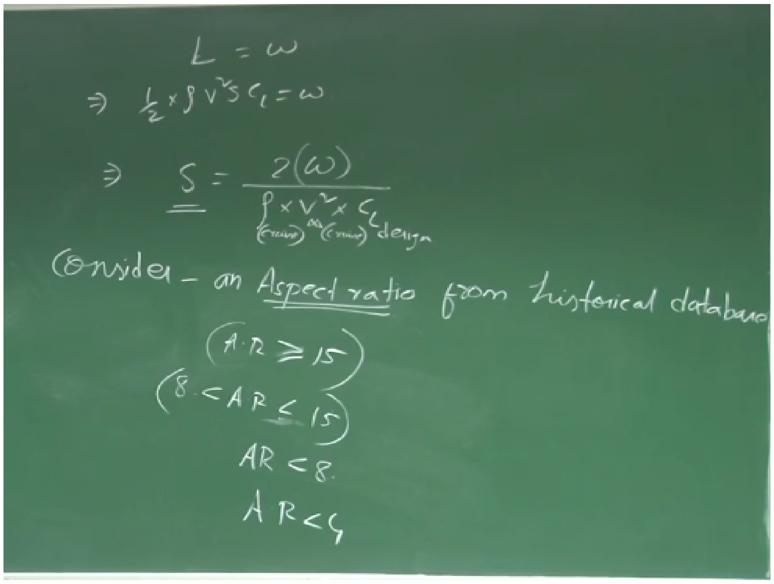

$L = \omega$

$\Rightarrow \frac{1}{2} \times \rho V^2 S C_l = \omega$

$$\Rightarrow \underline{\underline{S}} = \frac{2(\omega)}{\rho_{(cruise)} \times V^2_{\infty(cruise)} \times C_{L_{design}}}$$

Consider – an Aspect ratio from historical database

$(A.R \geq 15)$

$(8 < AR \leq 15)$

$AR < 8.$

$AR < 4$

So this 1/2 rho V square S*Cl=W, right. So S=2*the weight of the UAV* density* V infinity square*Cl design, right. So Cl design implies V cruise, right. So V cruise is an input and rho cruise is the cruise altitude. Generally, the parameter W/S is known as wing loading, right. It decides the velocity of your cruise, all the velocities, including take off, landing as well as cruise velocities.

So selecting this particular parameter during this initiation of the design depends upon some conditions like whether you want to design a hand launched UAV or you want to design an UAV that takes off with a short run up or do you need a UAV or if you are going to design a UAV, which has to run throughout the runway like, it will take a longer runway, longer distance for take-off.

The kind of; the type of UAV that you are going to design will help you to select the particular wing load. Say if you want to design a hand-launched UAV, the W/S ratio will be from 7 to 4. It is in Kg/m square, this is kg/meter square. So for a given weight where you can estimate the weight of the system by just assuming the L/D. The weight breakup is already done. You know the design Cl for the corresponding L/D and you know what is the cruise velocity and altitude from the mission requirements.

You will be able to estimate what is the initial estimate of what is the planform area that is required. Once you have this planform area, how to get the planform geometric parameters. So what are the planform geometric parameters? For example, we just measured the span of this wing, chord of this wing and we decide and we assumed that this is a rectangular wing, why? The chord at each point remains the same, right. It is of same length.

See at the root, it is of 0.23 meters even at the tip it is the same, but see if there is a variation at the root and tip, variation in the chord length at root and tip, then we call it as a tapered wing and then there can be a sweep and there can be a dihedral, the inclination of this wing with respect to horizontal is a dihedral. So these are the wing planform geometric parameters. So how to decide this?

In this first in this approach we are going to talk about the wing planform geometry as a function or aspect ratio as well as taper ratio. Assume an aspect ratio or from historical database, right. So what is this assumption or you can say consider an aspect ratio. So how to consider? This aspect ratio majorly classifies the UAVs into 3 different categories, 1 is acrobatic UAV, 1 is conventional UAV, or say which is of which is having a typical medium velocity UAVs and acrobatic is 1 which has higher velocity and higher maneuverability.

Medium velocity UAVs as well as glider UAVs, right where you want long endurance, higher endurance, that means you need the minimum power requirement. So the span should take care by itself. The span of the UAV should be sufficient enough to generate the lift at that particular altitude as well as the velocity and that velocity should consume the minimum energy. So that means, if you want to achieve a maximum endurance or the range long range, right, then you go for a design, which is close to a glider.

So long range UAVs are generally a glider UAV, has less long endurance UAVs are also glider UAVs, where they fly at very less velocity comparatively. So this aspect ratio classifies the type of UAV that you are going to design. So if this aspect ratio is anything greater than 15, you can consider it as a glider, that a particular UAV class belongs to a glider. For all those UAVs, which are having aspect ratio beyond 15.

So anything between say 14 or 15 till 8, it can be a medium-velocity UAVs. Their velocity of flight is higher compared to this UAVs. Anything < 8 is a low aspect ratio UAVs. So we also witnessed so acrobatic UAVs you can say and delta wing UAV, the aspect ratio will be around will be less than 4. This classification you can figure it out from any of the conventional text books, anyways I will present a slide for this.

Now aspect ratio has to be considered as an input based upon the type of UAV we are going to select and we have to iterate this aspect ratio, change this aspect ratio and figure out what will be the corresponding wing loading and taper ratio is also an input from historical database. Once you have this aspect ratio and lambda, taper ratio, you will be able to figure out what is the planform geometry major part of the planform geometry. So what is aspect ratio?

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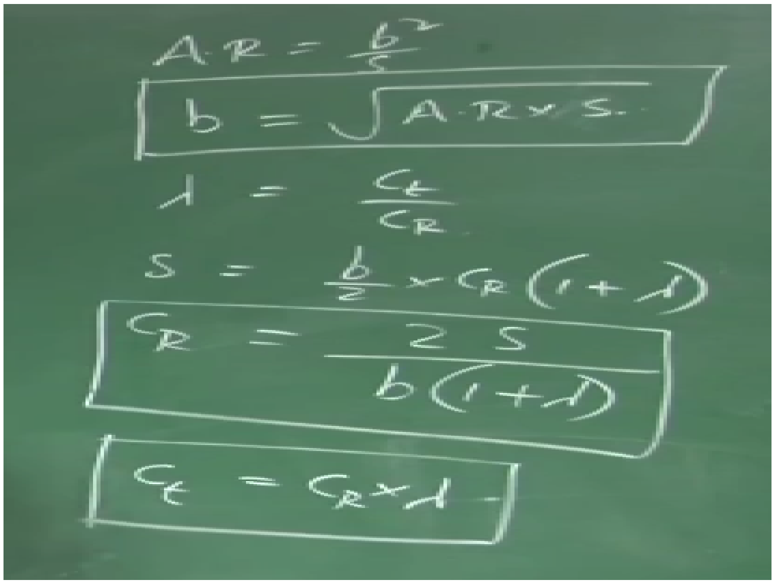

$$A.R = \frac{b^2}{s}$$

$$\boxed{b = \sqrt{A.R \times S}}$$

$$\lambda = \frac{C_t}{C_R}$$

$$S = \frac{b}{2} \times C_R(1+\lambda)$$

$$\boxed{C_R = \frac{2S}{b(1+\lambda)}}$$

$$\boxed{C_t = C_R \times \lambda}$$

b square/s, so corresponding span of the system will be. So now you have the span of the wing, aspect ratio* area planform area, other reference area and you have lambda equals to Ct/CR and what is the planform area as a function of lambda, span b/2*CR*1+lambda, right what you have is CR =twice the planform area/span*1+lambda. You will be able to identify or have an initial estimate of the span of the wing.

At the same time by considering the lambda, you will be able to figure out what is the root chord here. Now once you have the root chord, what will be the tip chord Ct=CR*lambda, so this particular parameter lambda will decide your tip chord as well here, right. So you have the root chord, tip chord, span, these are good enough to calculate the mean aerodynamic chord. How to calculate the mean aerodynamic chord?

Because ultimately we need to figure out what is the aerodynamic center of the wing, right. So how do you figure it. So that will be approximately 0.25 for a subsonic speed, like 0.23 to 0.26 of C bar for subsonic aircraft. So C bar = 2/3 CR*1+lambda+lambda square. So you can analytically estimate the C bar of the mean aerodynamic chord. With this C bar, you will be able to locate the aerodynamic center of this wing, approximately 0.25*of this mean aerodynamic chord.

Another information that you require is taper, right. So this taper is happening about a particular axis. You need to know the axis of taper. You should know what the corresponding axis of your taper. Now let us take a small example.

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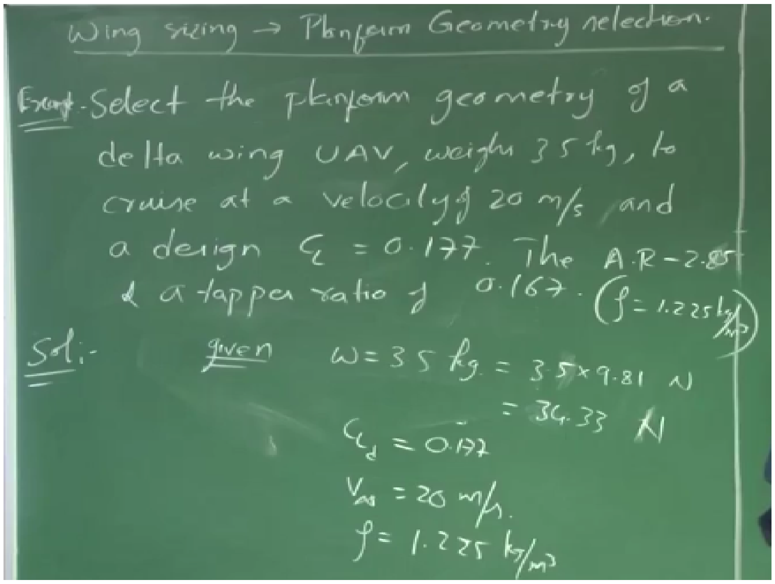

Wing sizing → Planform Geometry selection.

Exm. - Select the planform geometry of a delta wing UAV, weighs 35 kg, to cruise at a velocity of 20 m/s and a design $C_L = 0.177$. The A.R - 2.85 & a tapper ratio of 0.167. ($\rho = 1.225 \, kg/m^3$)

Sol:- given $W = 35 \, kg = 3.5 \times 9.81 \, N$

$= 34.33 \, N$

$C_{L_d} = 0.177$

$V_\infty = 20 \, m/s$

$\rho = 1.225 \, kg/m^3$

We will take the planform geometry of a delta wing UAV, weight is 3.5 kg, delta wing UAV to cruise at a velocity of 20 m/sec, right and a design CL, so it is cruising at a design CL of 0.177. The aspect ratio should be 2.85 and a taper ratio of 0.167, right. This UAV has to cruise at C level, consider C level, rho is 1.225 kg/m cube. So this UAV has to cruise at this particular altitude where the density is 1.225 kg/m cube.

Now we have to select a planform geometry of this. So first to figure out the planform geometry, we need to know what is the area of the wing should be. Once you have the area based upon this, aspect ratio and lambda, we can figure out the planform geometry of it. W=3.5 kg, which is 3.5*9.81 Newtons*34.33 Newtons and CL design=0.177 and the corresponding velocity is 20 m/sec, so cruise velocity is cube and density is here 1.225 kg/m cube, right.

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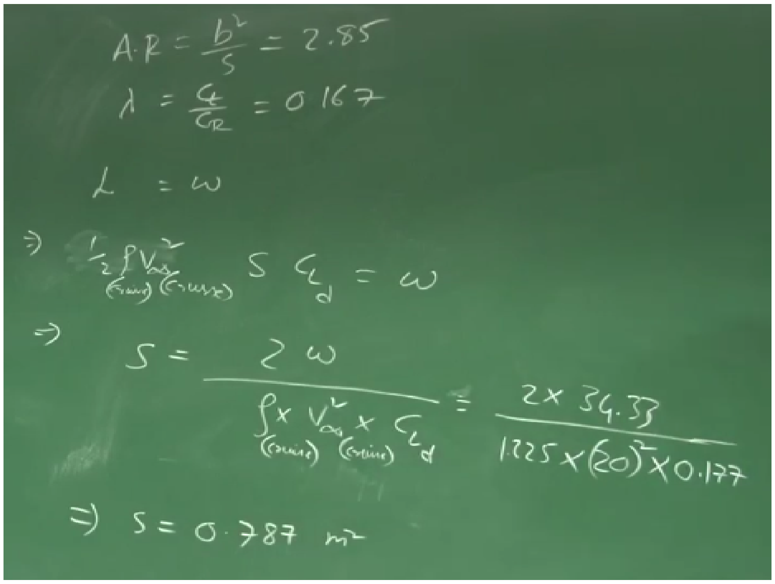

$$A.R = \frac{b^2}{S} = 2.85$$

$$\lambda = \frac{C_t}{C_R} = 0.167$$

$$L = W$$

$$\Rightarrow \frac{1}{2} \underset{(cruise)}{\rho} \underset{(cruise)}{V_\infty^2} S C_{L_d} = W$$

$$\Rightarrow S = \frac{2W}{\underset{(cruise)}{\rho} \times \underset{(cruise)}{V_\infty^2} \times C_{L_d}} = \frac{2 \times 34.33}{1225 \times (20)^2 \times 0.177}$$

$$\Rightarrow S = 0.787 \ m^2$$

Aspect ratio is given as an input, b square/S=2.85 and taper ratio lambda Ct/CR=0.167, right. Now let us figure out what is the planform area required to start with, right. For cruise, we have L=W 1/2 rho V square V cruise square, density at cruise altitude of rho V square*S reference planform/design CL=W. So the corresponding reference area is twice weight/rho*V infinity square*CL design CL.

This =2*substitute these values 34.33 newtons/1.225 is the sea level density since we are flying at sea level. So the corresponding velocity of flight is 20 m square*CL design. What is the design lift coefficient 0.177, S=0.787 m square. So this is the planform area that you require to lift this weight at this flight conditions. If you want to design a UAV of weighing 3.5 kg, with these performance parameters, you have to have an area of 0.787 meter square.

So once you know the area, you can calculate what is the span of this UAV.

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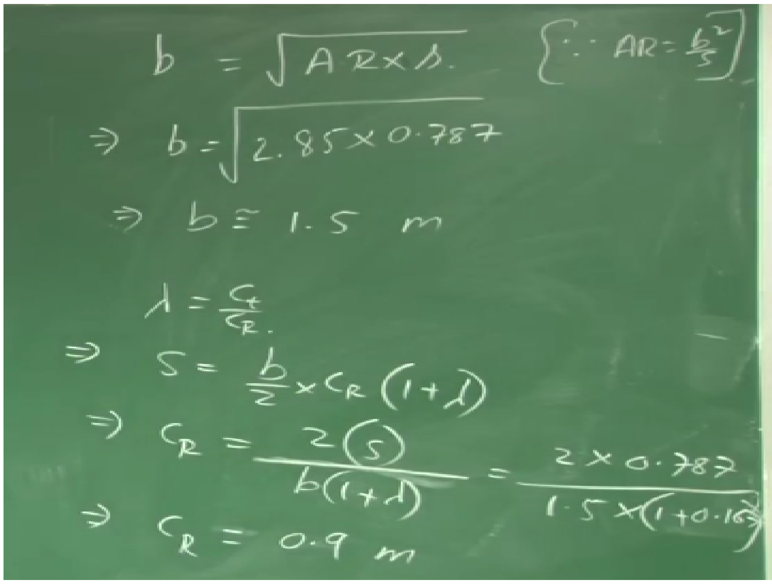

$$b = \sqrt{AR \times S.} \qquad \left[\because AR = \frac{b^2}{S}\right]$$

$$\Rightarrow b = \sqrt{2.85 \times 0.787}$$

$$\Rightarrow b \cong 1.5 \ m$$

$$\lambda = \frac{C_t}{C_R}.$$

$$\Rightarrow S = \frac{b}{2} \times C_R (1+\lambda)$$

$$\Rightarrow C_R = \frac{2(S)}{b(1+\lambda)} = \frac{2 \times 0.787}{1.5 \times (1+0.16}$$

$$\Rightarrow C_R = 0.9 \ m$$

So what is the span, aspect ratio*S because aspect ratio is b square/S, since AR=b square/S. So this implies span of this UAV should be 2.85*S is 0.787. This implies the span of this UAV is 1.5 meters approximately. This should be approximately 1.5 meters' span. Another information that you have here is lambda Ct/CR. So we have area=b/2*CR*1+lambda, CR=twice the reference area/span*1+lambda.

So CR=0.9 meters approximately, which is twice 0.787/1.5 meters*1+0.167. So the root chord is 0.9 meters. So since we know the root chord, by using the definition of taper ratio, you can figure out what is the corresponding tip. Ct=CR*lambda that is 0.9*0.167=0.15 meters, right.

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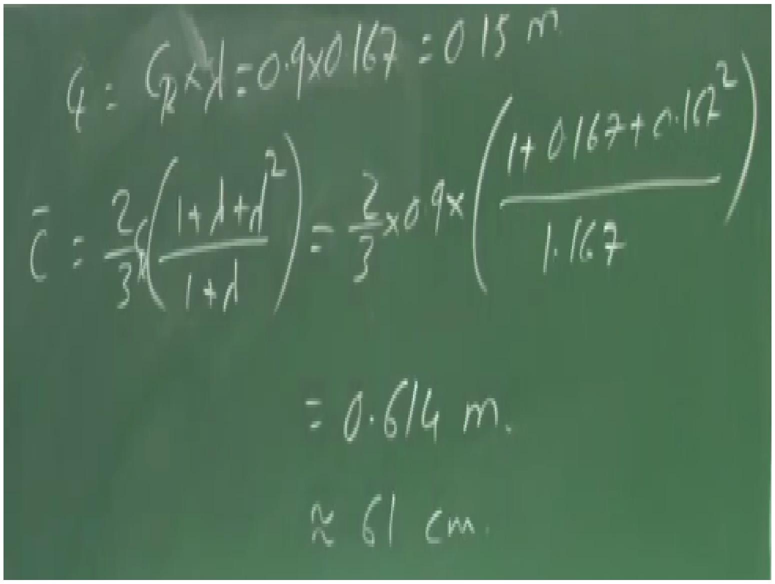

$$C_t = C_R \times \lambda = 0.9 \times 0.167 = 0.15 \text{ m}$$

$$\bar{C} = \frac{2}{3} C_R \left(\frac{1+\lambda+\lambda^2}{1+\lambda}\right) = \frac{2}{3} \times 0.9 \times \left(\frac{1+0.167+0.167^2}{1.167}\right)$$

$$= 0.614 \text{ m.}$$

$$\approx 61 \text{ cm.}$$

You have Ct, you have CR, you have the span, what will be the mean aerodynamic chord. C bar is 2/3 CR*1+lambda+lambda square/1+lambda, implies 2/3 CR*1+0.167+0.167 square/1.16, 0.614 meters is the approximately 61 cm.

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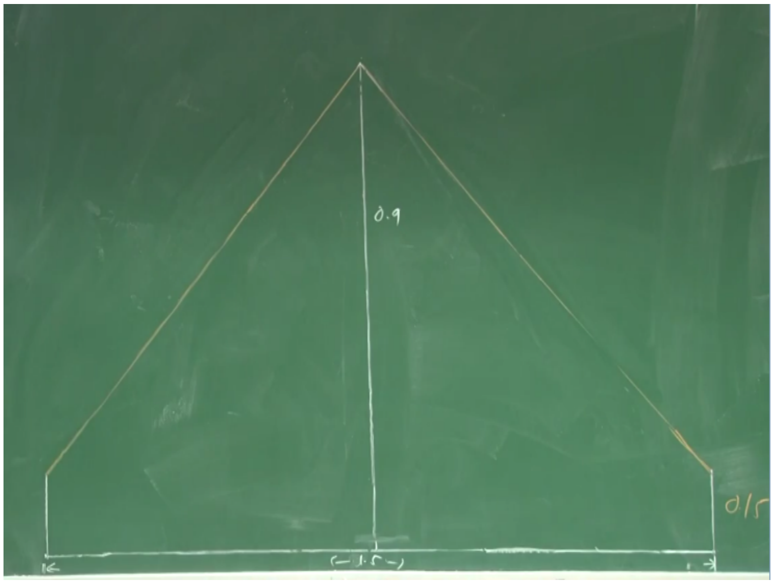

S is 0.787 m square, b is 1.5 meters, CR is 0.9 meters, Ct is 0.15 meters, and C bar is 0.614 meters. To start with, I have to draw 1.5 m wing, this is 1 m, this is half a meter. I have 1.5 meter span here, right. So what should be the root chord for this, where it should be, at 0.75, so this is your 0.75 of it. This overall span is 1.5 meters, 0.75 have CR is 0.9. So assuming this is perpendicular, like this line is horizontal and I made this face perpendicular to it.

So this is my root chord, right. joint the leading edge of root chord in the tip chord, what we have is a delta wing, right of 1.5 meter span and Cr of 0.9 meter, 0.15 meters of tip chord, right. So since in the position it is mentioned it is a delta wing, we directly tapered it about the trailing edge. Otherwise we need to know the axis about which it is tapered, right. So tapered is about trailing edge, that means the trailing edge of this root chord and the trailing edge of the tip chord should lay along the same line, right.

So this is the planform geometry and we will show the flight test of this particular design, particular UAV, right. Now what should be the mean aerodynamic chord of this particular planform.

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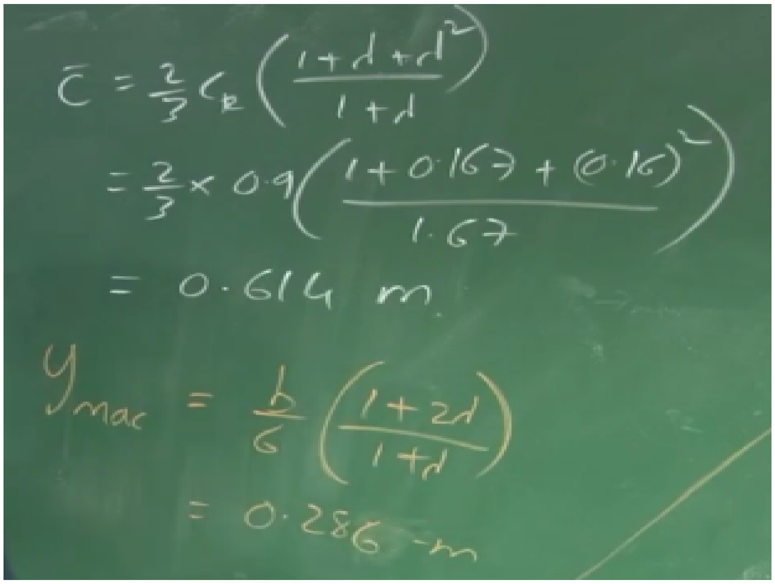

$$\bar{C} = \frac{2}{3} C_R \left(\frac{1+\lambda+\lambda^2}{1+\lambda}\right)$$

$$= \frac{2}{3}\times 0.9\left(\frac{1+0.167+(0.16)^2}{1.67}\right)$$

$$= 0.614 \text{ m}$$

$$y_{mac} = \frac{b}{6}\left(\frac{1+2\lambda}{1+\lambda}\right)$$

$$= 0.286 \text{ m}$$

So we have C bar=2/3 CR 1+lambda+lambda square/1+lambda, that is 2/3. What is CR 0.9*(1+0.167+0.167 square)/1+0.167. This is 0.614 meters. Let us see what is this 0.614 meters, so what is the mean aerodynamic chord. It is a chord at a particular location, where your chord length is 0.614. So where it is, 0.614 approximately. This is the mean aerodynamic chord in my case. In this particular case, this is the mean aerodynamic chord, which is 61.4 cm.

This is the mean aerodynamic chord, right. Similarly, you will have a mean aerodynamic chord this side. What should be the location of that. Y (mean aerodynamic chord) =b/6*(1+2), this 0.2857 meters or 0.286 meters is 28.6 cm, right, is it. So this is full scale, right. It should be almost equal to the same. See it is approximately 28 cm from here. So project this on to the root chord, project this MAC.

Similarly, you will have mean aerodynamic chord this side well. So you project it on to the root chord, so finally this is going to be your mean aerodynamic chord. So in this case for a delta wing, since the trailing edge of root chord as well as the tip chord lies on the same line. You can easily locate the aerodynamic center.

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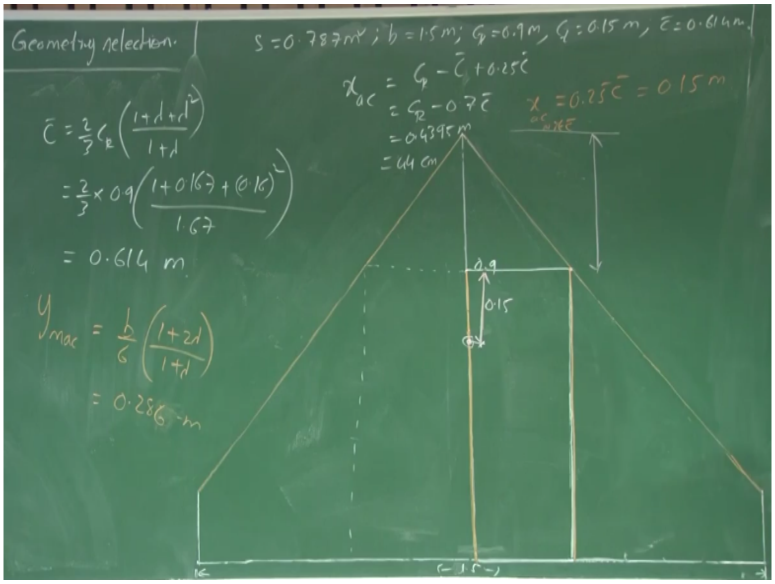

So Xac=CR-Ct or C bar CR – C bar + 0.25 C bar. What does it mean, what I am doing here? I subtracting this mean aerodynamic chord from the total chord of this configuration, root chord of this configuration. That means what you have is this length. So plus I need to know what is the corresponding aerodynamic center. So the aerodynamic center here is 0.25 of this C bar, that is quarter chord of the C bar. So this is my 0.25 C bar, so what is 0.25 C bar of this.

So Xac with respect to C bar=leading edge of the C bar is 0.15 meters, that is 15 cm from here. Here it should, so this is 15 cm. This is 0.15 meters from the leading edge of this C bar, right. To measure this, it will be difficult, right. You do not know physically where this C bar is present. So it is easy to mark this aerodynamic center with respect to the leading edge of the root chord. So what you need to do. You need to add this distance plus this distance, right.

So to get this distance, you need to subtract C bar from the root chord. Say this is your C bar, subtract this from the root chord, you get C bar sorry CR-C bar + this distance. It is the quarter chord point of C bar. So this is going to be C bar-CR-0.75 C bar. So this is approximately 0.4395 meters, which is 44 cm, approximately 44 cm. So it should be; So you can simply have a tape and measure the corresponding mean aerodynamic center of this configuration, which should be approximately at 44 cm from the leading edge of this root chord, right. You can look at it physically, right.

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Wing cross section : Flat Plate
Wing planform : Cropped Delta Wing
UAV Lab, Department of Aerospace Engineering, IIT Kanpur.

These are the 2 UAVs that is with the same planform what we have discussed. 1 is a flat plate configuration, the other 1 is a reflex wing configuration. That means the profile is rectangular cross section here for the first configuration.

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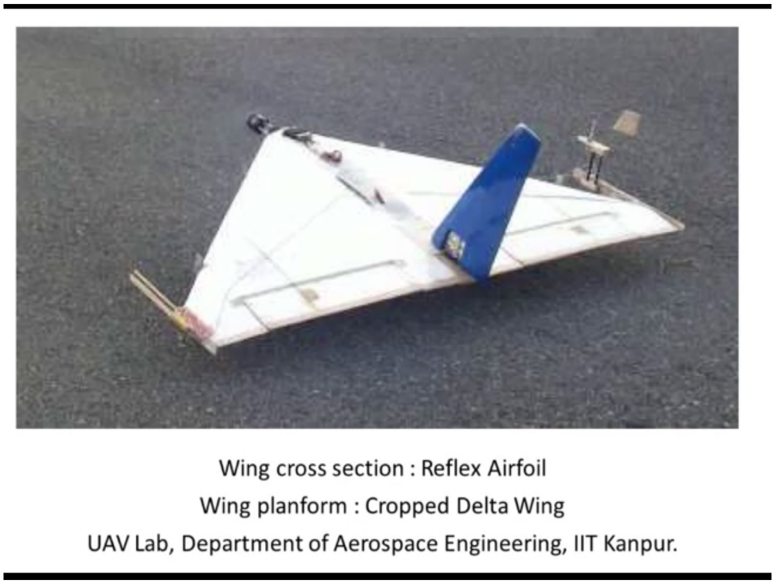

Wing cross section : Reflex Airfoil
Wing planform : Cropped Delta Wing
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The second 1 is with a reflex aerofoil cross section. The aerofoil that is used here is NACA23110.

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Flight test of
Flat-Plate Cropped Delta Wing
UAV

Wing cross section : Flat Plate
Wing planform : Cropped Delta Wing

UAV Lab, Department of Aerospace Engineering, IIT Kanpur.

Let us witness the flight test of these 2 configurations.

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Flight test of Reflex Cropped Delta Wing UAV

Wing cross section : Reflex Airfoil

Wing planform : Cropped Delta Wing

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