Design of Fixed Wing Unmanned Aerial Vehicles
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Lecture - 03
Anatomy of Airplane and Airfoil Nomenclature

Good morning friends welcome back. In our previous lecture, we were talking about how to find the velocity of UAV right.

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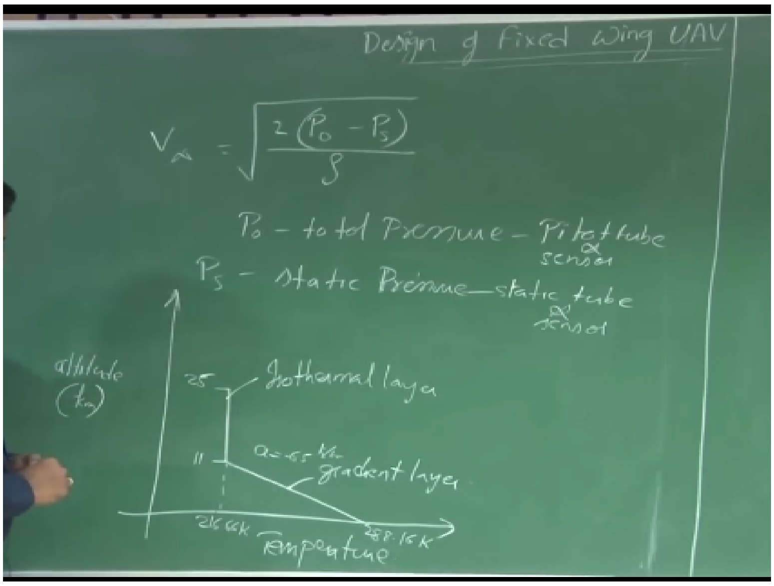

So we derived that if you know the differential pressure that is if you can measure the total pressure, static pressure and if you know the density you will be able to find the velocity. So we measure this total pressure right with the help of pitot tube and static pressure with the help of static tube and corresponding pressure sensor, static tube right connected to a pressure sensor, static pressure measured with the help of static tube connected to sensor pressure sensor.

And to know the density at that particular altitude right we derived standard atmosphere equations for standard atmosphere. So where we observed there are some altitudes at which like the temperature changes with altitude and the pressure and density also changes with and standard atmosphere is a plot that represents the variation of this temperature with altitude right.

So let us limit ourself right now to the first two layers. This is a gradient layer and the slope is=-6.5 Kelvin per kilometer. So this gradient layer extends up to 11 kilometers altitude and this is the sea level, this is the temperature variation and the sea level temperature is 288.16 Kelvin right and up from 11 to 25 kilometers it is observed that the temperature almost remains constant and the corresponding layer is termed as isothermal layer right.

So at 11 kilometers we observed it is 216.66 Kelvin right yes. So to find out the temperature pressure and density at different altitudes we have derived for gradient layer.

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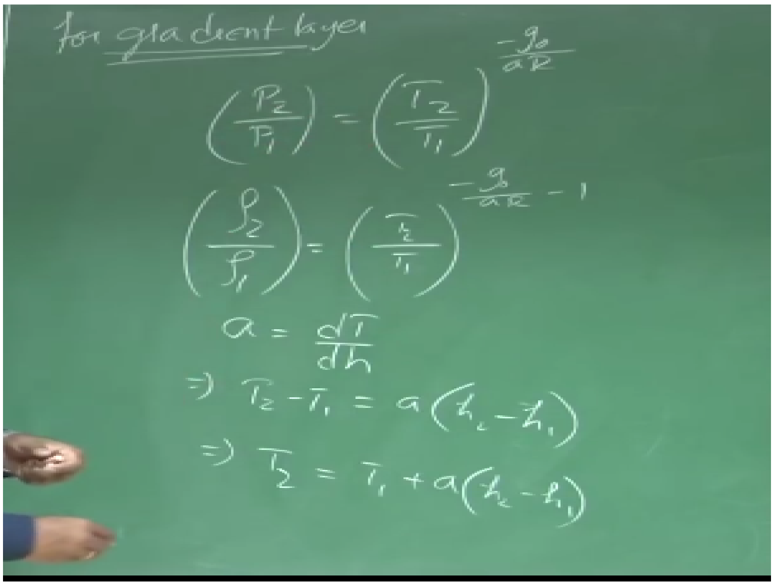

We can use this equations or relationships aR, aR-1. So these two relationships stands for gradient layer where if you know the altitude you can find the corresponding temperature at that particular altitude by the definition of this lapse rate which is dT/dh, this=T2-T1 is=a*h2-h1. T2=T1+a*h2-h1 right. If you know the altitude of your flight, you will be able to find out the corresponding temperature right.

So using this temperature and the sea level temperature and you know the sea level density you will be able to find out the density at the required altitude as well as the pressure at the required altitude. So what are these STP conditions?

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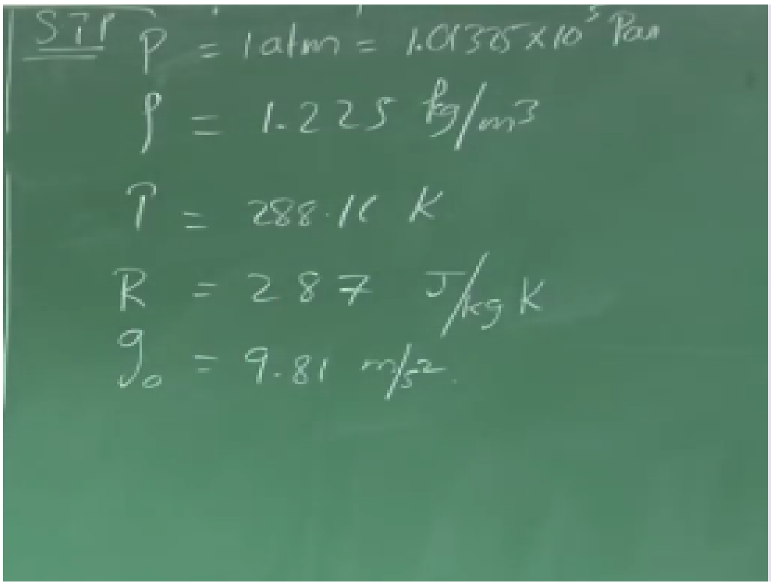

Standard temperature pressure P at sea level right at STP of sea level you have P at 1 atmosphere which is 1.01325*10 to the power of 5 Pascal. At STP we have density is=1.225 kg per meter cube and temperature is 288.16 Kelvin and the R that we are using here is you know is a gas constant, it is 287 joule/kg Kelvin and g0 is 9.81 meter per second square okay.

Now yesterday we solved few examples right in which we assume that the dense altitude is known, altitude is given and the corresponding velocity is obtained right by means of the measured either pitot pressure or the static pressure now but who is giving this information about your altitude, how do you know at what height your UAV is flying. So in our previous examples, we considered altitude is given right.

But how do you know who is going to give that? Let us take some examples so to address this right.

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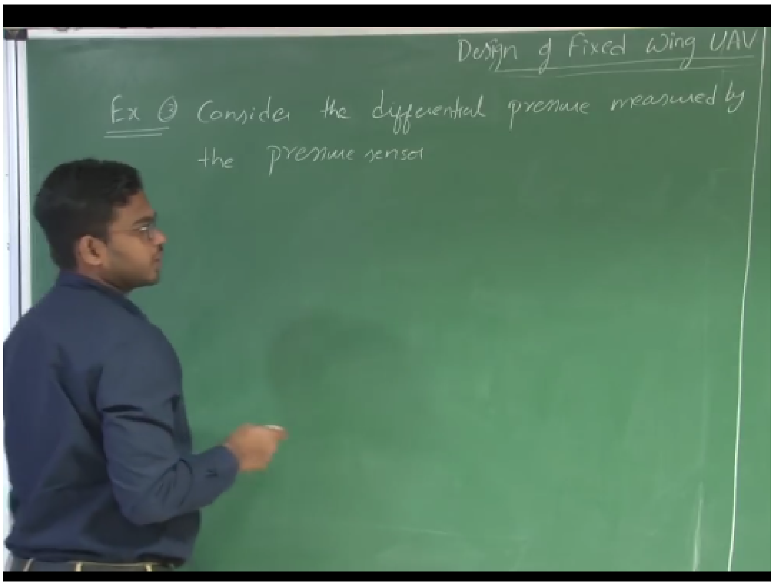

Example 3 if I am not wrong, consider the differential pressure measured by the pressure sensor, so in some cases we can also have differential pressure sensors right.

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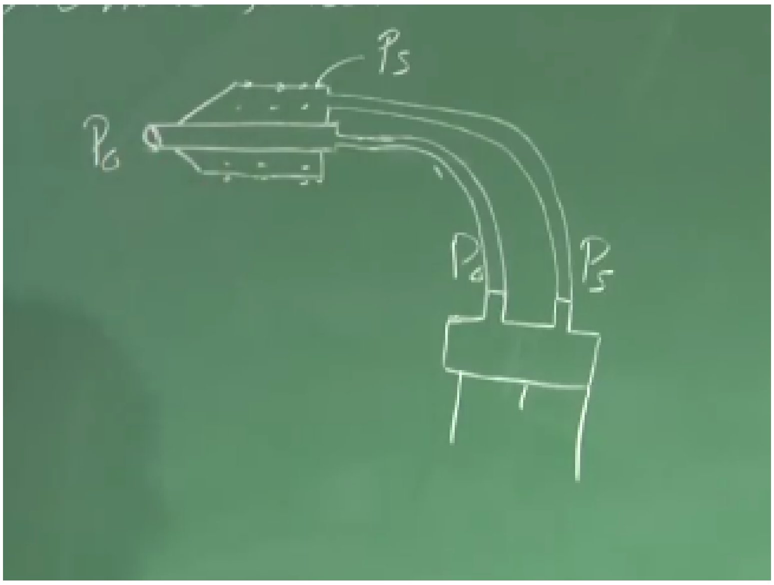

Instead of measuring pressure separately from pitot tube and static tube what you can do is you can connect to a differential pressure sensor right. One can be P0, the other can be Ps. So you can have a pitot tube, you can connect pitot tube to this total pressure port and then you can have a static tube at the same time. So we will get Ps from here, P0 from here right. So you can use a differential pressure sensor directly.

So this differential pressure is measured by this differential pressure sensor right.

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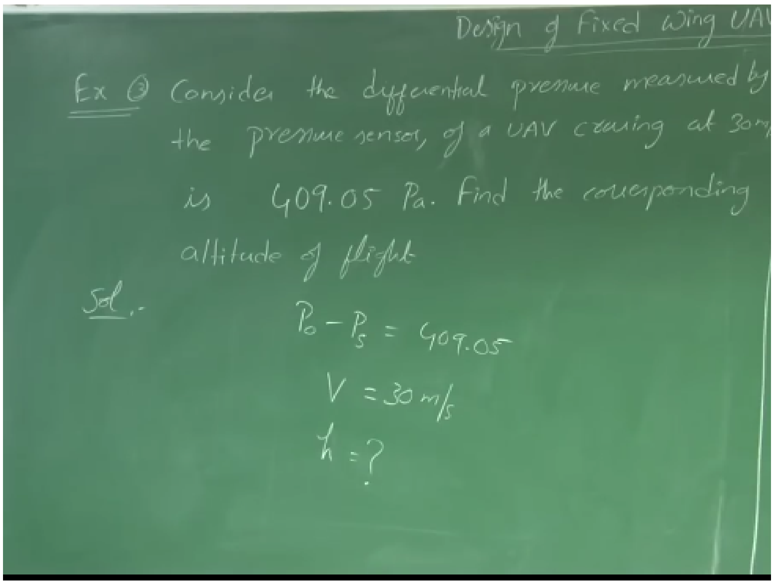

So the difference is of a UAV cruising at 30 meter per second is 409.05 Pascal right. Find the corresponding altitude of flight? Right the question is clear here. We have P0-Ps is=409.05, you have cruise velocity is 30 meter per second. Now you need to find what is the altitude at which you are flying? So let us consider ourself like all the examples that we are going to solve is for the gradient layer till 11 kilometers right, so even commercial aircrafts fly till 11 kilometers.

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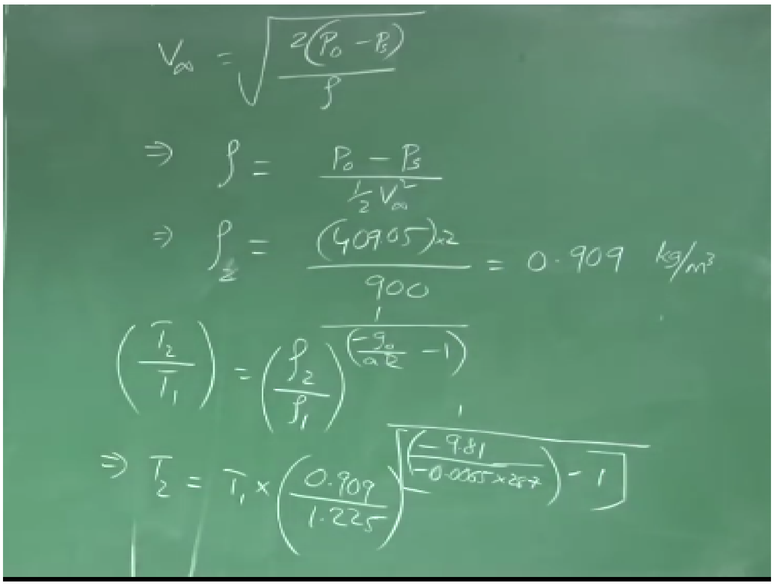

Now we have V infinity is=square root of 2 times P0-Ps/rho right and say if I want to find out h right either I need to know what is the density at that altitude or the pressure at that altitude, static pressure at that altitude. So let us see what we can find from this given data. Rho is=P0-Ps/1/2 V infinity square. From here I can get what is the density because P0-Ps is 409.05 twice/900=0.909 yes almost like 0.909 kg per meter cube.

Now I know density at high pitch right or say let it be the density at our altitude right, it is at the corresponding altitude of the flight. Now using this relationship what we have is T2/T1 is=rho 2/rho 1 1/-g0/aR-1 right. T2=T1 times what is rho 2 is 0.909/1.225 kg per meter cube, so rho 1 is here sea level density and T1 is a sea level temperature-9.81/-0.0065*287-1.

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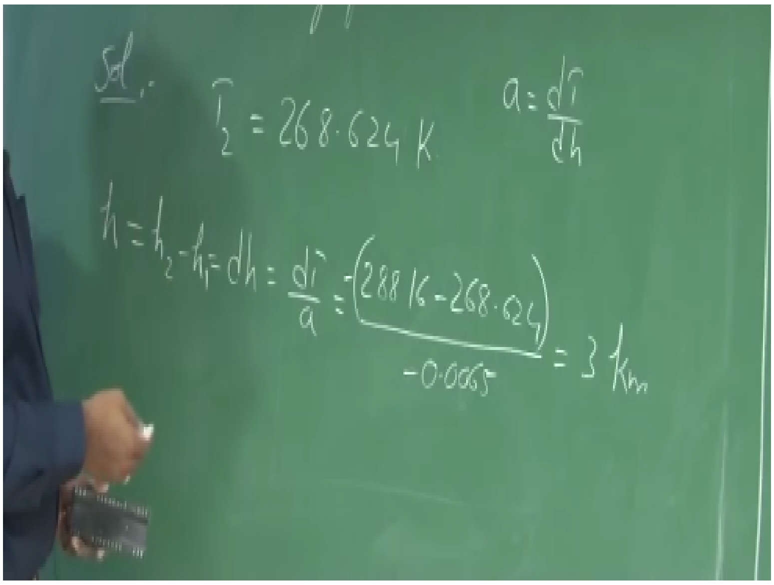

So what we have T2=288.16, what we get from here is 268.624 Kelvin right. You know T2, by using the definition of lapse rate you can find what is the h since you have dT you can find dh right. So using the definition a=dT/dh right dh=dT/a that is=288.16-268.624/-0.0065, this is – of – T2-T1, this is T1 and T2 right, this equals to which is approximately 3 kilometers, so this is h2-h1 which is h right because h1 is 0 here sea level condition.

Now you got geopotential altitude as 3 kilometers right, now you have to convert this 3 kilometers to geometric altitude.

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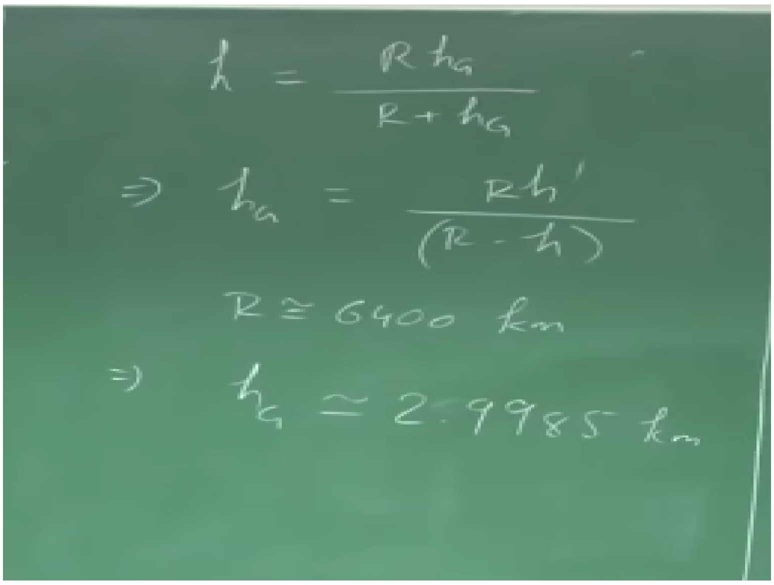

We have h is=R*hG/R+hG right, this implies hG is=R*h/R-h right, so R here is approximately 6400 kilometers radius of earth, R is the radius of earth here, so hG turns out to be 2.9985 kilometers. So the difference is hardly 1.5 meters right, difference between geometric altitude and geopotential altitude.

Assuming that there is no on-board GPS with which I mean that is one source where you can get the altitude of flight right assuming that there is no on-board GPS now with the absolute pressure whatever you are going to measure right how to find out the corresponding altitude. So this problem will address that situation right. So let us take another example.

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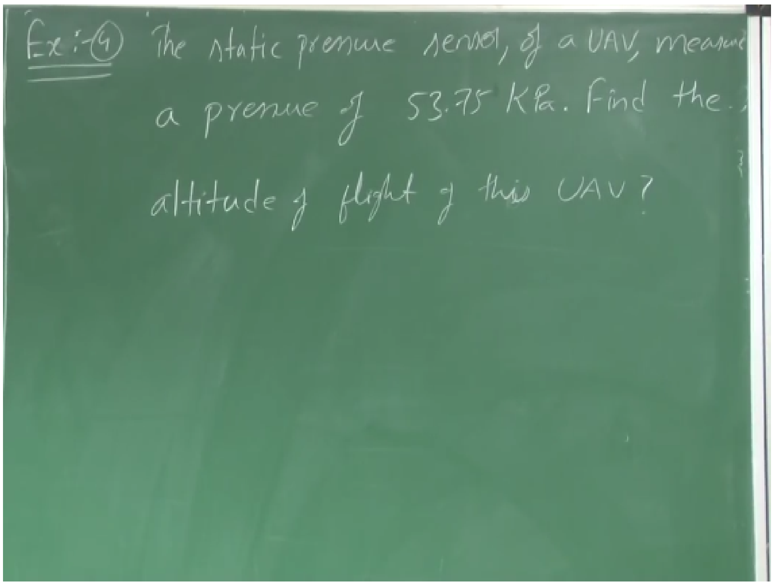

Example 4, the static pressure sensor of the UAV measures a pressure of 53.75 kilopascals. Find the altitude of flight of this UAV?

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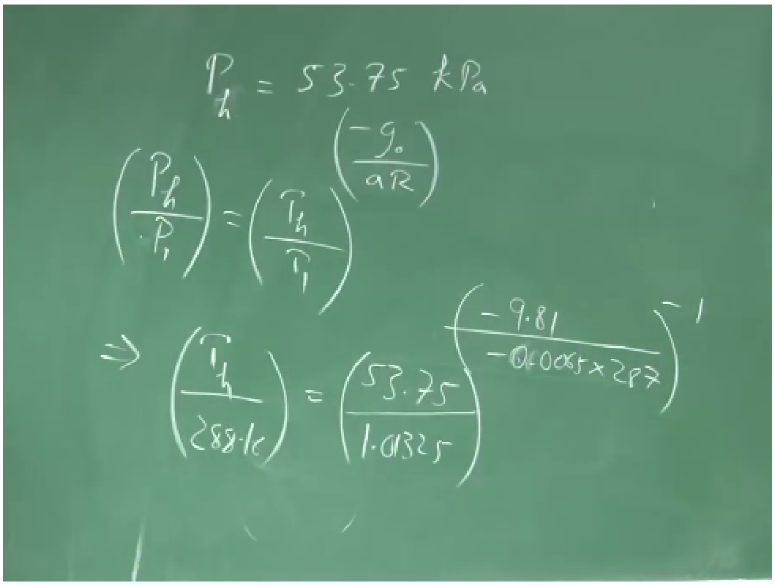

So what you have here is Ps a static pressure or P at a particular altitude h right is=53.75 kilopascals okay. Now we need to find out the corresponding altitude of flight. So we can use this relationship Ph/P sea level right P1 let us say is=T at that altitude/T at sea level raised to the power of –g0/aR right. This is T at that altitude/288.16 is=53.75 kilopascals/1.01325 kilopascals raised to the power of -9.81/-0.0065*287 right.

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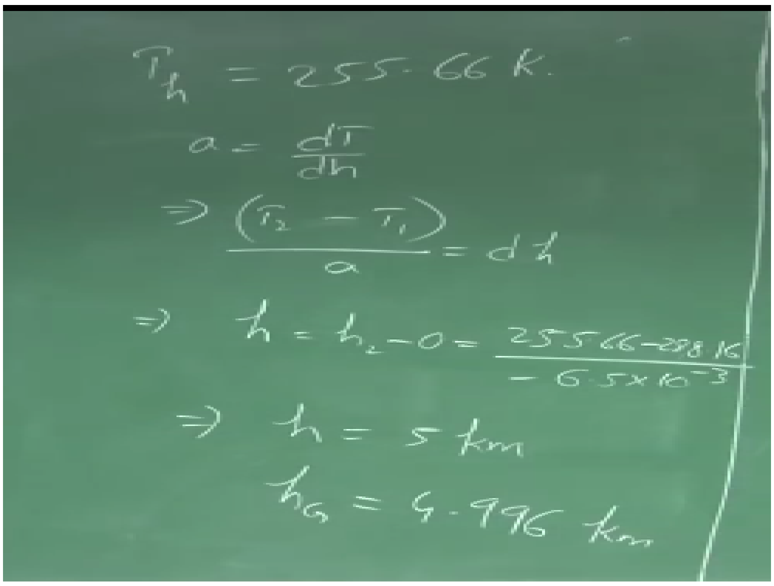

Now the temperature at this altitude is=255.66 Kelvin right. So we know from the definition of lapse rate again a is=dT/dh right we have T2-T1/a=dh right that is h=h2-0=255.66-288.16/-6.5*10 power -3 which is=5 kilometer right. So the corresponding hG is 4.996 kilometers right and the corresponding geometric altitude is approximately 4.996 kilometers. So what you have done here?

In the question, it is mentioned we have a static pressure data from the sensor which is about 53.75 kilopascals by using this static pressure we found the corresponding temperature at that altitude right by using gradient layer equation and with the help of definition of this lapse rate we are able to find out the corresponding altitude of flight and this geopotential altitude turned out to be 5 kilometers.

And with the help of the relationship between geopotential altitude and the geometric altitude, we figured out geometric altitude to be 4.996 kilometers. Now let us look at an aircraft.

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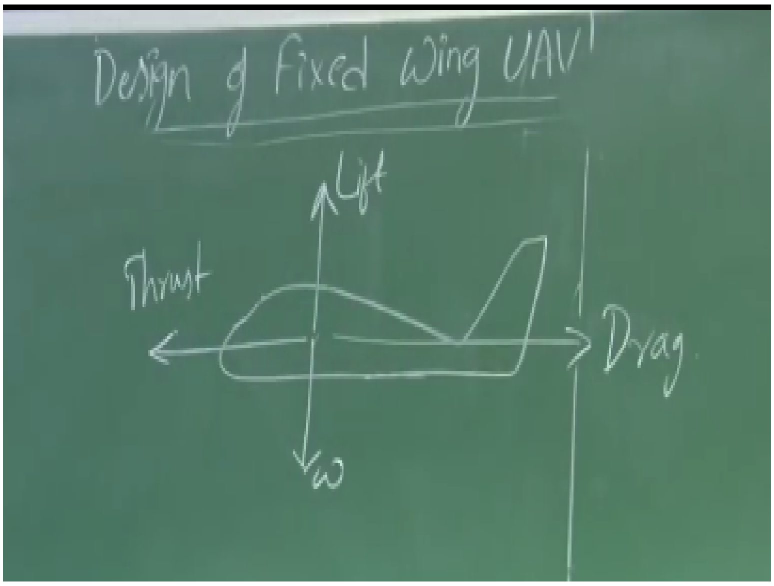

Let us say this is my UAV which I am interested in okay yeah fine. So why do this aircraft fly? One simple answer can be there is some force which is opposing this rate right. Let us term this force as lift right and how lift is generated, since we are talking about fixed wing UAV we need to move this aircraft at a required velocity. Who is moving this aircraft? Thrust is the force that is helping the aircraft to move at the required velocity right.

And there is some penalty at the same time for generating lift as well as since we are moving in a fluid right there can be friction so because of which there is an opposing force called drag. These are the 4 forces that we need to study here right, first to understand before start designing it. Now who is generating lift? Now let us look at the anatomy of the aircraft right.

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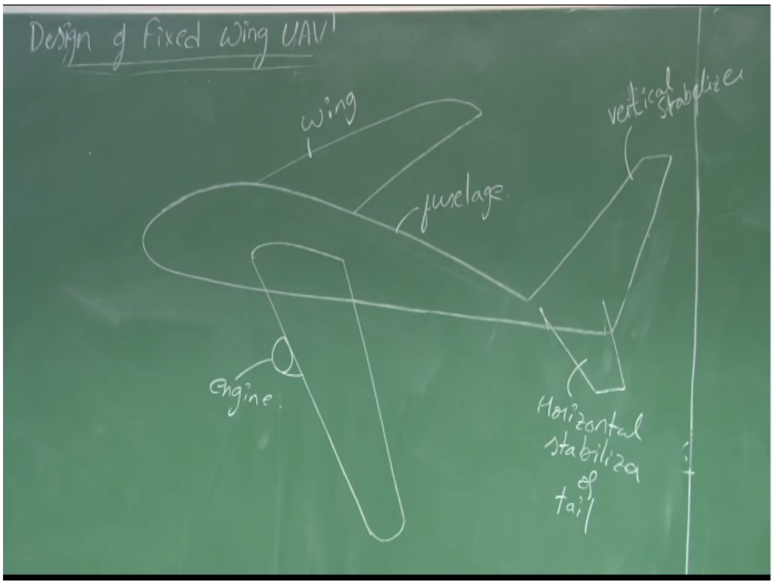

So let us assume this as an aircraft right. So you have so the major components are wing, horizontal stabilizer or tail, vertical stabilizer or vertical tail right and we have a propulsion system that is engine, here it will be on either side right. You can have a single engine as well in some of the aircrafts. So you have fuselage and then undercarriage right.

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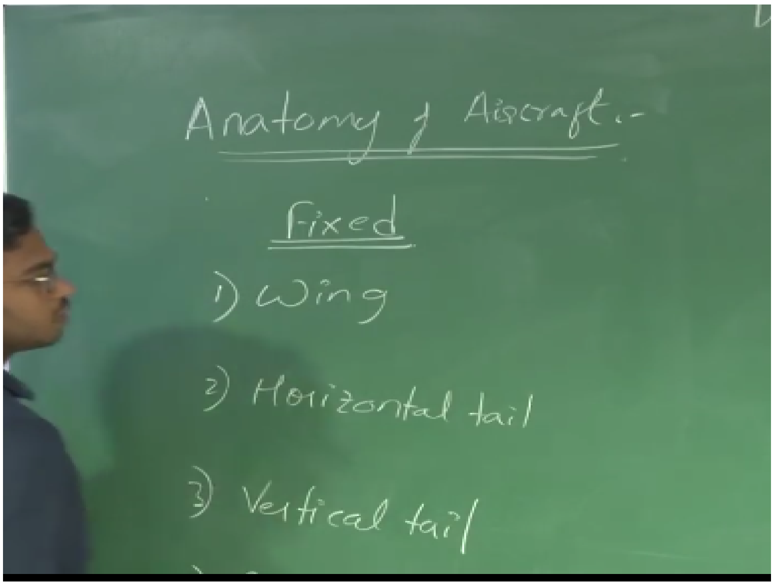

Now major components which are fixed let us say for a conventional aircraft what are the fixed components and what are the moving components right. So fixed is like you have wing, you have horizontal tail, you have a vertical tail, fuselage right. So we also have some moving components right. So why do we need them? To control the orientation of this aircraft.

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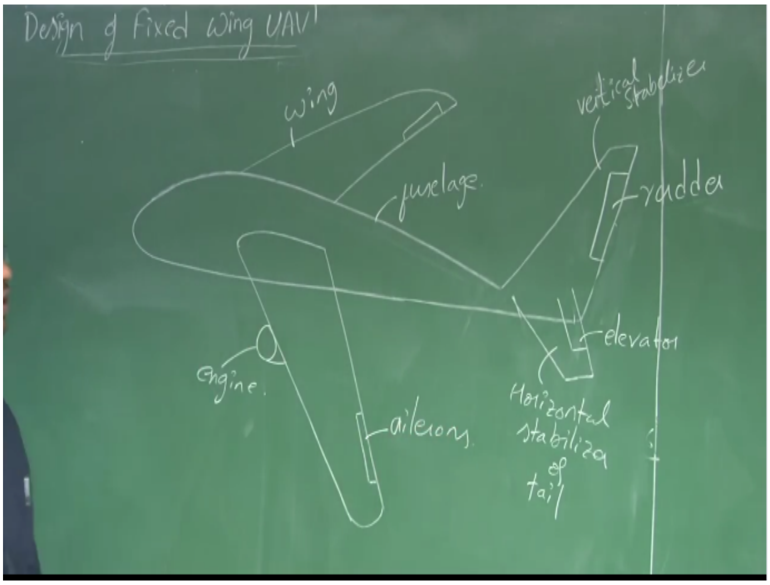

So hence these moving components are also known as control surfaces. Some of these moving components are known as control surfaces right. So we have something on elevator as well as so we have something on horizontal tail called elevator, it is a moving surface right which helps to control the nose up and nose down motion right and there is a moving component on this vertical tail called rudder which helps you to turn left and right.

And there are control surfaces on wing as well as ailerons which helps you to roll right. So we need to mention various motions that are possible with an aircraft, it is worth mentioning here right. So aircraft is considering it as a rigid body right and rigid body in space have 6 degrees of motion right. What it can do? It can move, it can translate.

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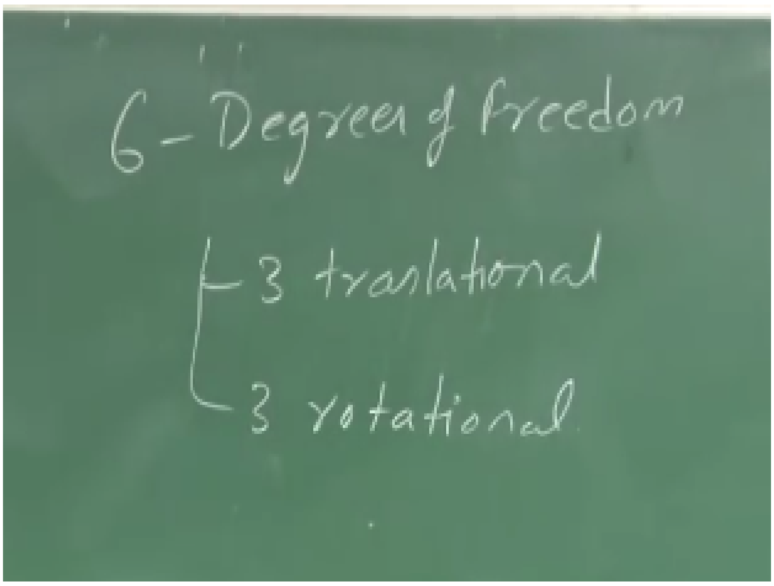

So total it has 6 degrees of freedom, 3 translational 3 rotational right. So this rotational or the orientation of this aircraft can be controlled by this control surfaces.

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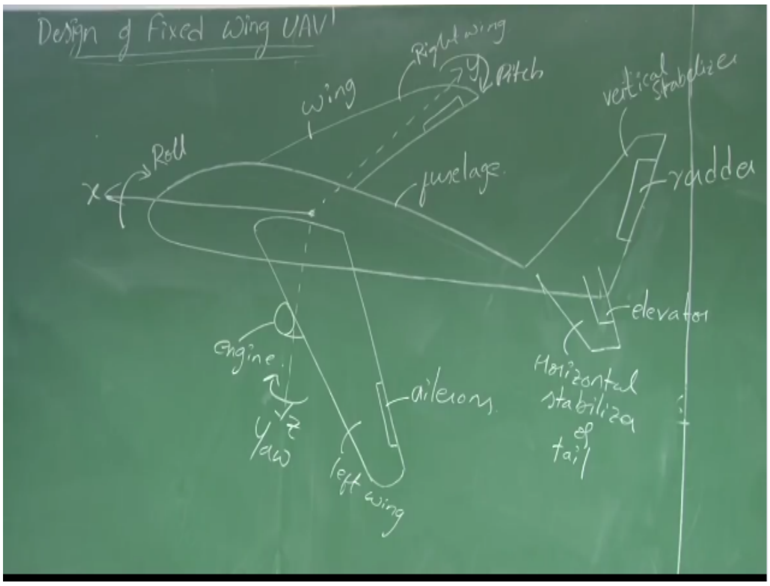

So assuming this as the CG of the system and be the origin of this coordinate frame whatever I am considering now right. Let us consider a right-handed coordinate system right where x cross y is here. So the translational along x, along y, along z are the I mean other 3 degrees of freedom right linear translation and then there is an angular rotation possible here. So let us start with x axis, the rotation about x axis is known as roll right.

What is the positive roll now? We have to define the convention also right. So it follows the right hand thumb rule, stretch your free thumb along the positive x axis, the curl of your fingers will give the positive rotation about the respective axis. Now the positive roll will be this is a right wing say starboard and the left wing or port side right. So right wing going down is a positive roll right.

So you have roll right. Similarly, this roll is controlled by this ailerons right. You can control the rolling motion by deflecting the corresponding control surfaces called ailerons here right and what about rotation about y axis known as pitch right pitch. So the positive pitch will be nose up. If the nose is going up, it is a positive rotation about y axis. If the nose is going down, it is a negative rotation about y axis.

Similarly, you have yaw right. If the right wing coming back, it is a positive yaw, so pitch rotation about y axis can be controlled by elevator. We will see how we can do that at a later stage right. At the same time, yaw can be obtained by means of rudder deflection right okay.

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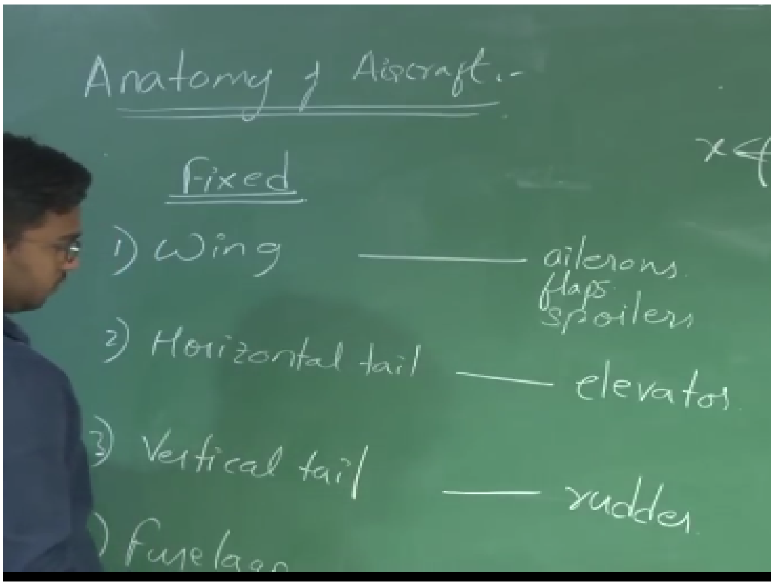

So the moving surfaces we have with wing is aileron for control.

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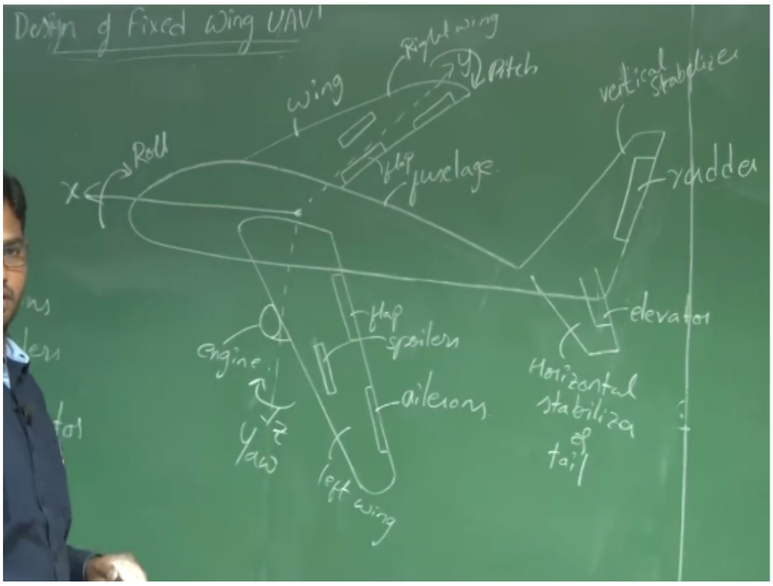

And you have flaps or high lift devices which are used to enhance the lift right. We saw that lift is essential, we nomenclature just now a force that opposes the weight right. So lift so if you want to enhance the lift at a lower velocities, we need to operate this flaps right and you have flaps at the same time you also have spoilers which can sometime be used as a control surface as well, you also have spoilers.

So the basic aim of this spoiler is to reduce the lift, disturb the flow yeah and increase the drag okay and how about horizontal tail what do you have is an elevator, it can be a split elevator as well right. You can have 4 such split elevators to have the differential control right there and you have vertical tail chord and the corresponding control surface known as rudder right.

So how to control the speed? So one variable that we have here, one control that we have is by varying the thrust right. So thrust is often considered as a control input okay right. So we just now saw wing is one of the major component right of this aircraft right.

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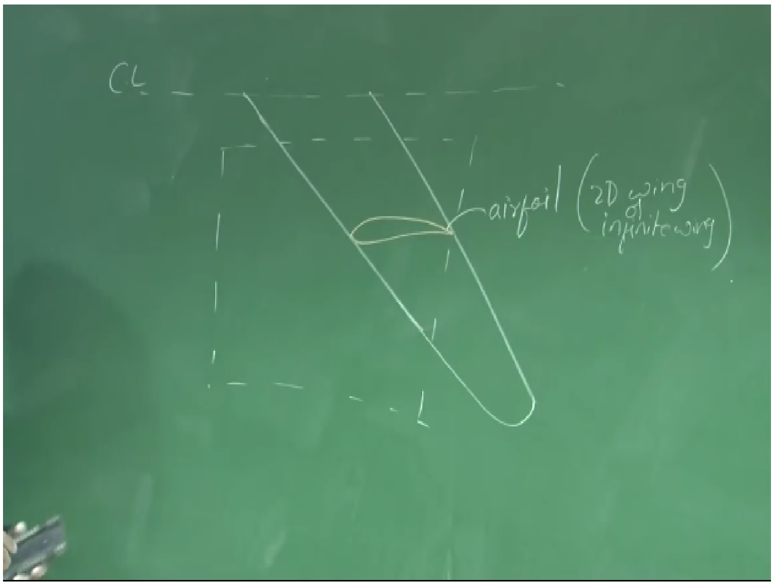

Let us cut this wing, let us say this is your some say center line or fuselage reference line right. Let us say this is your wing right. What happens if I cut this wing? We will often find a profile similar to this right. So this profile is known as airfoil which is a 2D wing or infinite wing, 2D wing or infinite okay. So this airfoil is responsible for generation of lift, how efficient you I mean how efficient the lift will be right.

So you can there are many ways to generate, you can also use a flat plate right. So this shape speaks a lot about how efficiently you can generate the lift right. So let us look at the nomenclature of this airfoil first.

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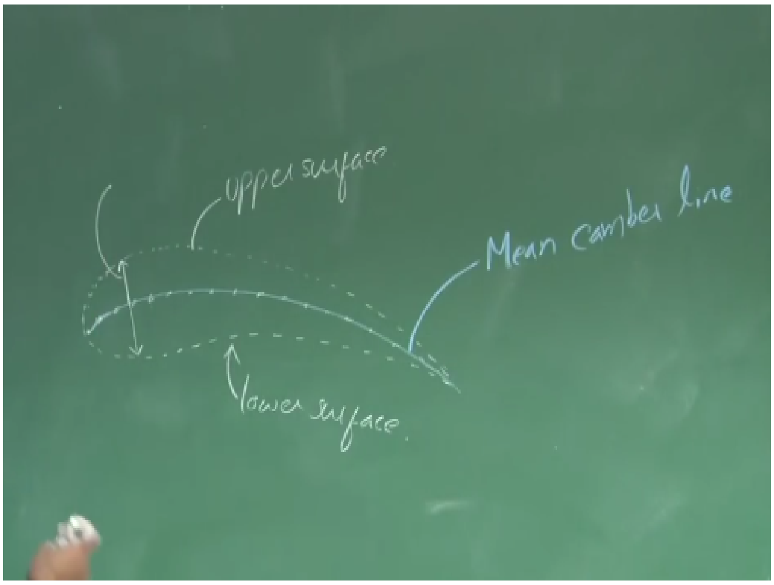

So let us consider an arc or a line like this alright. Let us say this is let us nomenclature it as Mean camber line. What is this mean camber line right? Now if I want to draw an airfoil with the help of this mean camber line what should I do? I can build the entire airfoil with the help of this mean camber line right. So let us say I know the thickness distribution at each and every point right.

Thickness is measured perpendicular to the mean camber line at that particular point right. Now say if I have series of points because if I vary the points along this camber line I will get the thickness distribution. Let us say if I have that information right, I will be able to plot upper and lower boundaries right. These upper and lower boundaries are my upper surface and lower surface of airfoil right.

And now obviously since this thickness is the distance measured right from the upper surface to the lower surface perpendicular to the mean camber line right. So here the thickness distribution is symmetric about this mean camber line right you understand. So this mean camber line will be the midpoints of the thickness at that particular location right. So mean camber line can be defined as locus of midpoints of thickness of an airfoil right.

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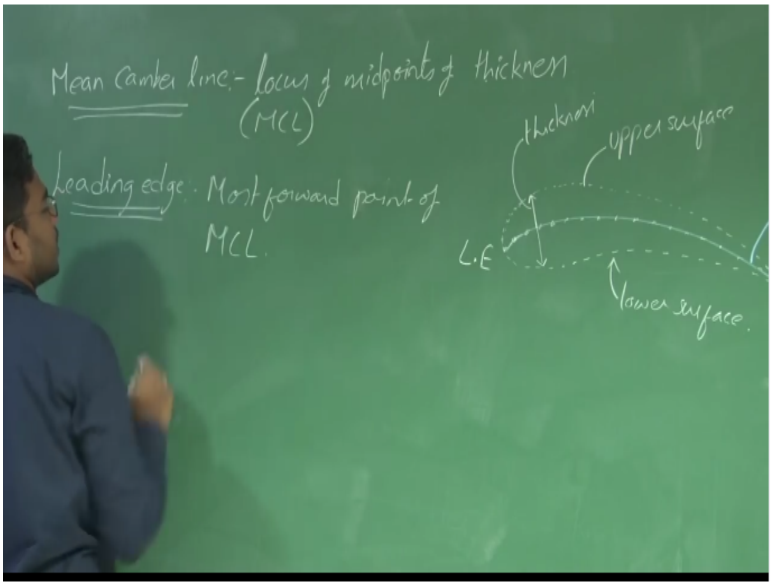

So it is a locus of midpoints of thickness right and you have upper surface and lower surface here and you have thickness which is the distance between upper surface and lower surface which is measured perpendicular to this mean camber line and the starting point of this mean camber line is a leading edge. So mean camber line or camber line, write MCL and the after point of this mean camber line is trailing edge right.

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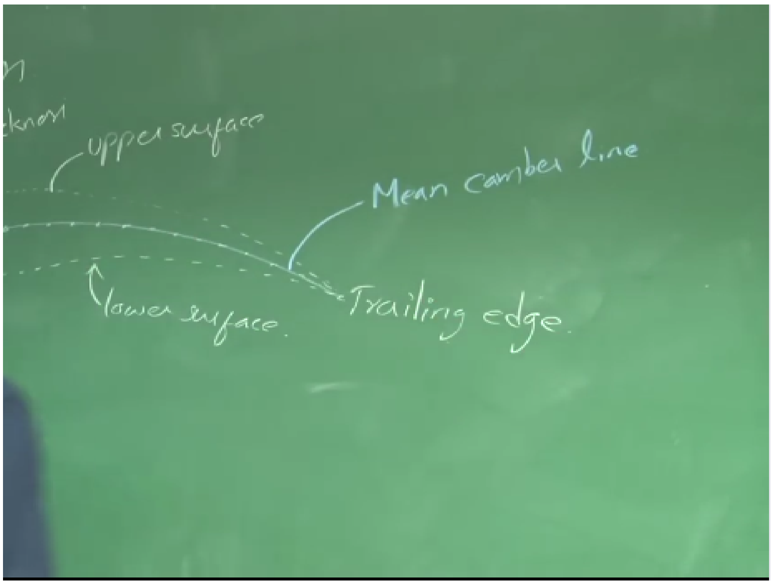

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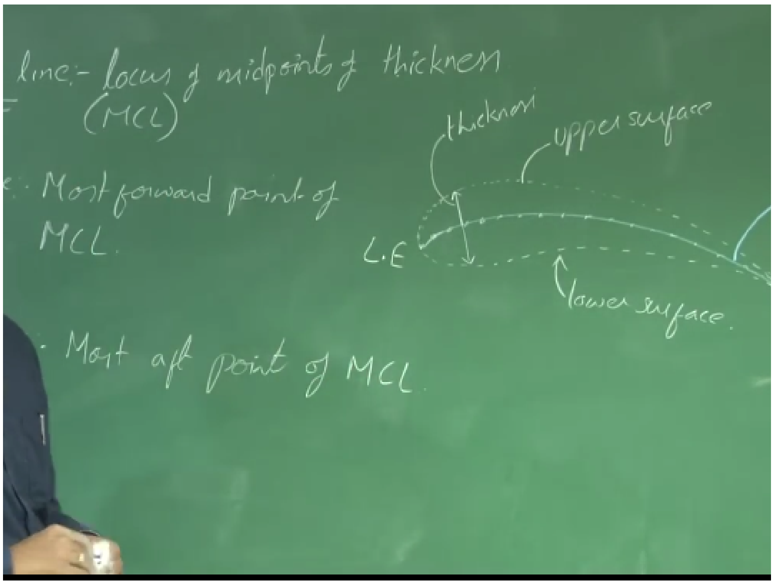

Straight line joining this leading edge and the trailing edge is known as chord line.

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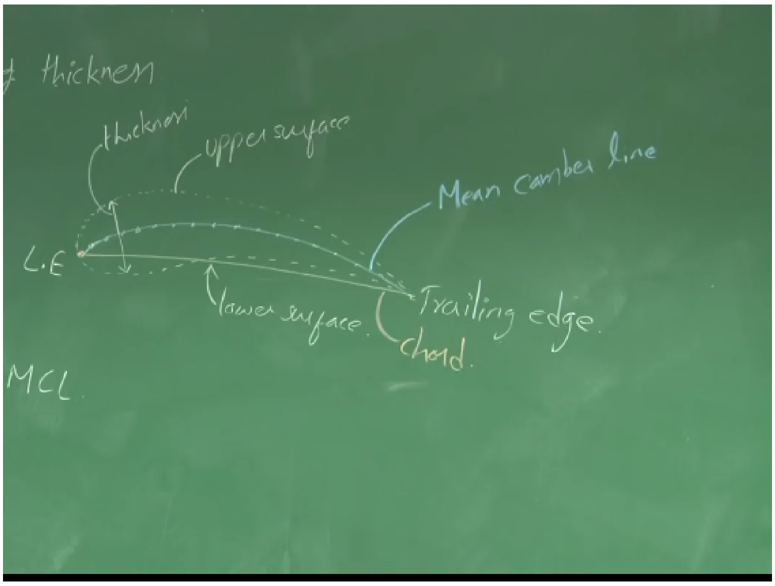

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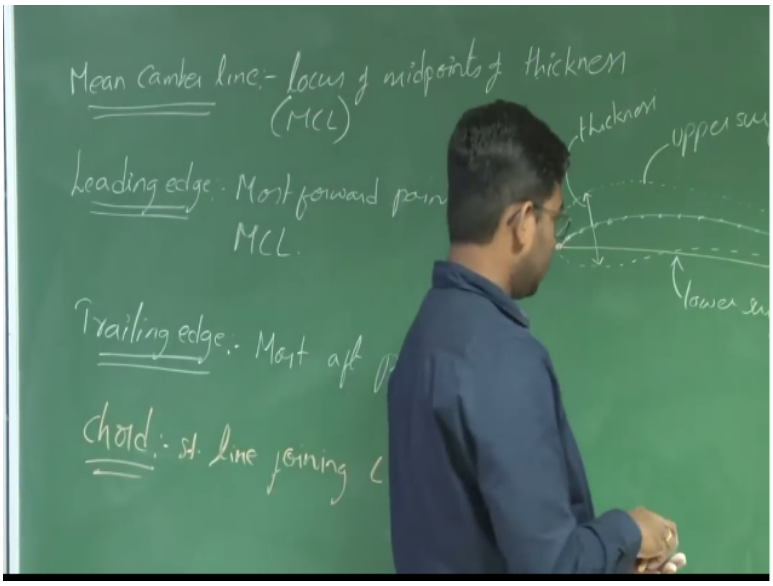

This is my chord. Straight line joining leading edge and trailing edge right.

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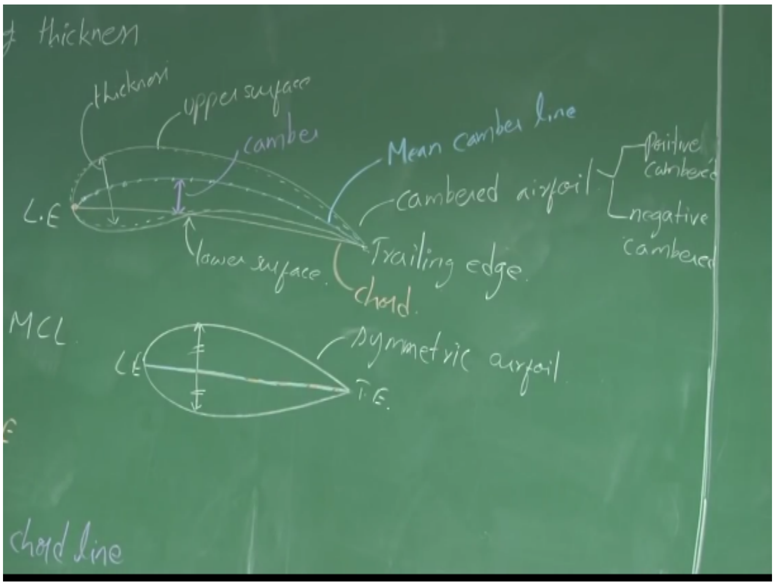

Now comes the camber, the distance between this mean camber line and chord line is known as camber, mean camber line and chord line right okay got it. Now say if the camber is 0 what happens? What is camber 0? When the mean camber line coincides with this chord line, so in that case the thickness distribution will be symmetric about chord line.

So when there is camber the thickness distribution is always symmetric about mean camber line but it is not symmetric about this chord line right when there is a camber but when camber is 0, the thickness distribution is symmetric. So it is like the upper surface is a mirror image of bottom surface about the chord line right. So in that case this is how an airfoil look like.

This is your chord line and this is your mean camber line both coincides with each one right so and you have equal thickness distribution. These two are equal right. This is your leading edge; this is your trialing edge right. This particular airfoil is known as symmetric airfoil. So this airfoil is known as cambered airfoil because it has a camber, cambered airfoil right. So if this camber is above the chord line then it is known as positively cambered airfoil right.

If this camber is below the chord line, then it is known as negatively cambered airfoil. So you have two such airfoils known as positively cambered and negative cambered, positive cambered and negative cambered airfoils right. If I make a wing out of this symmetric airfoil I have a symmetric wing and if I make a wing out of this cambered airfoil I will have a cambered wing right.

So let us see how to plot an airfoil. Ultimately what do you require? You require upper surface and lower surface that is it right and something called leading edge radius right.

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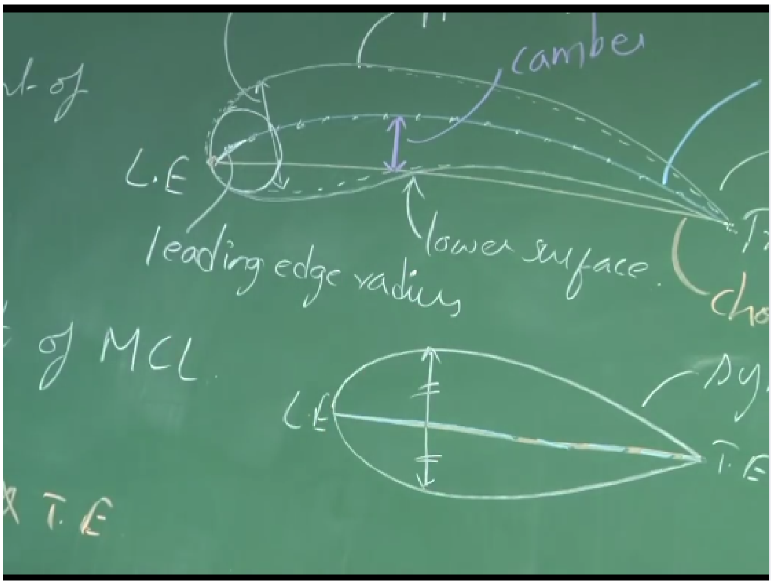

So this curvature which is tangent to the upper and lower surface right is known as leading edge. If you draw a circle with a radius such that the circle becomes tangent to the upper and lower surface alright. So that radius is known as leading edge radius. We call this as leading edge radius okay. Now how can I plot this airfoil? When I say plot here, I need the coordinates of upper and lower surface. How can I plot it? Or say how an airfoil often works?

Say if you want to design a new airfoil what all you need to do? Right you have to start it. So the information that I require is you can see the camber is varying with respect to the mean camber line is varying as the chord varies alright. Let us say you have a chord here, at each and every location of this chord this there are corresponding coordinates for this mean camber line right.

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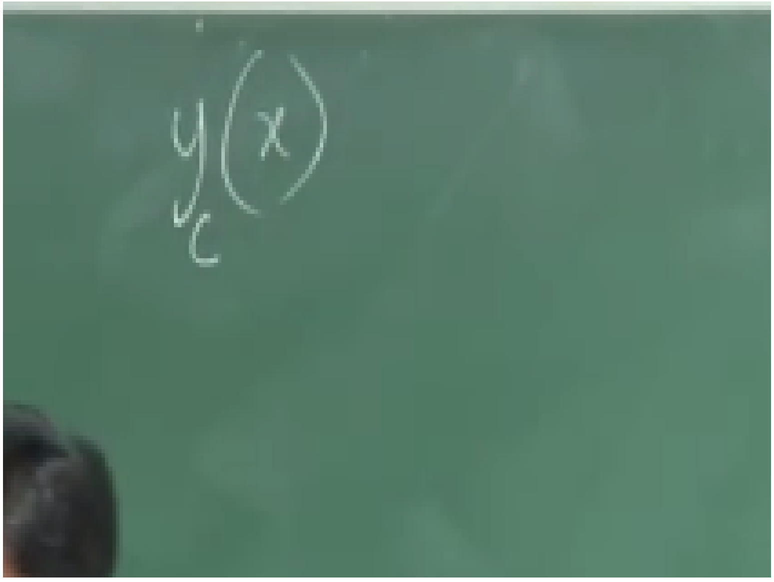

Say if I have the coordinates of the mean camber line. Say this is let us say c is my mean camber line, yc as a function of chord or say x right okay.

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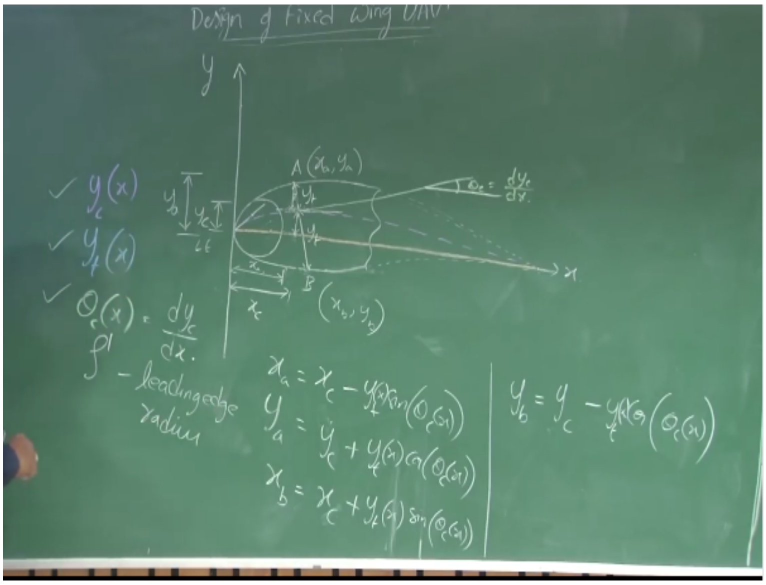

Say this is my y axis and this is my x axis right. Now let us assume the chord is along this x axis okay fine. So let us consider my chord is along this x axis right and if I know the equation of this mean camber line right and if I have an equation that talks about the distribution of thickness at each and every x, at each and every x if I have the corresponding thickness distribution about y about mean camber line okay.

And if I know the slope at each and every point of this mean camber line, I will be able to plot this airfoil right. What do I require here? Let us say this is my chord of this airfoil as well okay. Now for different locations of chord what I require is what will be my y of camber line at that corresponding x right, y of thickness at that corresponding x and theta of the camber line at that x.

If I have this information, then I will be able to figure out what is the corresponding upper and lower surface right, coordinates of upper and lower surface. So let us see how? Right. Now let us consider point on the x axis on the like let us consider point on the chord right and the corresponding let x on the chord right. Now what will be the corresponding point on the camber line?

From this you will get to know what is the corresponding point on the camber line right, so this is my corresponding coordinate of the camber line. Now I know the slope here because theta of the camber line at that particular x I know right. If I draw a tangent right theta of c is=dyc/dx okay. If I draw a tangent at this point right, so now thickness is perpendicular right. Thickness is measured perpendicular to this mean camber line.

So if I have to draw the thickness, I need to know what are my, no what is my if I have to draw perpendicular I need to know what is the reference here right. The reference here is the tangent right. So perpendicular to this tangent, I have this y of t, see although this need to be more closer. So that it look symmetric right, so consider this is a symmetric understand, symmetric thickness distribution.

Although, it does not look like but please consider this right. Now you have this as y of t and the same y of t you have it here. Now what are these coordinates there? Right, so if I draw a local horizontal here which is parallel to this right say this is my white line which is parallel to this. So this is parallel right, so this perpendicular component, so these two will be perpendicular and the corresponding angle will be theta here right.

This angle will be equal to this angle whatever I have right and y of t if I have a cos component of it right you will get this height and you know this height right. So this is let us say this point is y of c, x of c right. This height is this particular height I have here is y of c, this is x of c, so I get this y of c from here, for a particular x I know what is my y, y of the mean camber line right.

Now the point A say and there is a point B where I have xa and ya and xb and yb right. So xa=I know this total distance, if I know this distance say this is my x here, this is my x here right. If I know this distance if I subtract this otherwise to get this x here if I know this distance and if I subtract this distance right. I know what is xc, if I subtract this horizontal distance right, I will get to know what is my xa. So xa is=xc-yt sin theta of c at that particular x, yt at that particular x right.

What is y at point a? Is yt, sorry is yc, this is horizontal right, so parallel to this line this distance plus this distance, this is again perpendicular to this line correct. So this total distance will be this is ya right which is summation of yc+this particular distance. So yc+yt of cos theta of c at that particular x right. Similarly, what is xb? So this distance plus this distance right xa+yt of x*sin theta of c at that x and similarly yb, yc-yt*cos of theta of c at that particular x okay.

Got it right, now if you look at this see yc is how much? yc is this much, yt is this much like yt cos component is this much here, yt is this much and yb is this much, no. Okay so from here right I need to get to know what is the coordinate from here because I am calculating this entire length I know this length if I want to know this length with respect to this chord then I have to subtract here right.

So what happens is this becomes a negative quantity that is why you have negative axis, negative y axis here. Here it is a negative y axis okay. So assuming the chord line is your x axis then you will get the negative y coordinate there right. So you have xa, ya and xb, yb. So at each and every point you can find out the corresponding upper and lower surface coordinates for a given chord correct or for a given point from the chord right.

Are we done? What about leading edge radius? So consider this is my leading edge and you know the slope, at that particular point draw a tangent right, draw a tangent to this mean camber line at that particular point with the slope equal to the slope at that particular chord location right. Now measure the radius along this chord line and draw a circle by using that point as a center.

Although, it is not exactly the same, draw a circle so that should become tangent to the upper and lower surface right. So this becomes the leading edge radius okay. So to define the airfoil what we need is equation of mean camber line or camber line and equation for thickness distribution as function of chord right and theta of the slope of this camber line as a function of chord and the leading edge radius says it rho prime right. Rho prime is your leading edge radius okay.