Aircraft Design
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Lecture - 13
Design Considerations: Wing

Good morning friends, in the last lecture we have seen we are being mostly talking about nomenclature of aerofoil knock aerofoil, nowadays there are many customized aerofoils which are most of the time trade secret for different different manufacturing company design and manufacturing companies. But as a designer let us come out of that nomenclature and related things, what is more important for a designer to understand an aerofoil in a simplistic manner. So, that it helps in not only in selecting an aerofoil, but also making this aerofoil part of a wing finally, whatever aerofoil you are using or selecting that has to become part of a wing.

So, let us go little more deep as a designer perspective is concerned, and see what could be a designers perspective reserve is those aerofoils or database etcetera available.

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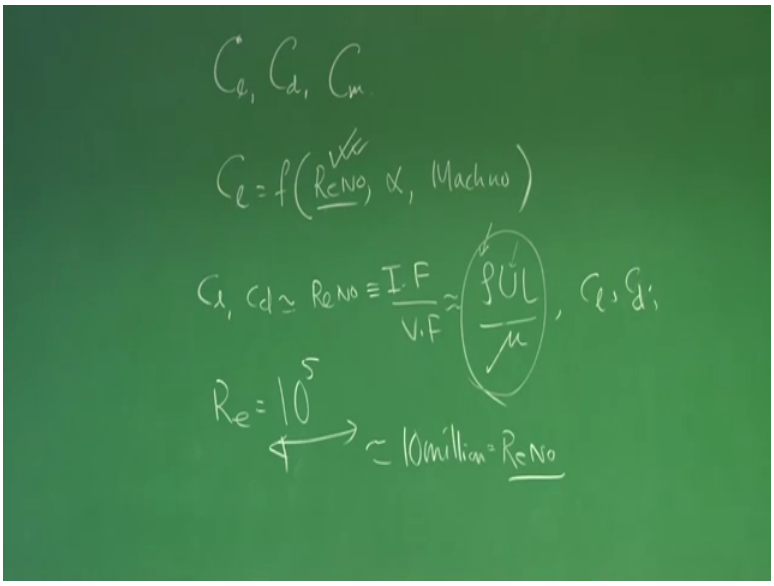

First let us not forget we are talking about C l, C d and then some part C m these are all aerofoil characteristics. And you know from our first course a C l will be the function of Reynolds number alpha mach number I will focus more on reynolds number as a designer if I have to design an airplane I need to know what is the design altitude and what is the design crew speed. Why that is important because I know the C l C d they vary with Reynolds number, I know it is ratio of inertia force by viscous force and you can write it like rho UL by mu.

So, as I am going higher and higher altitude because rho is changing even if I give you same, if even if I assume viscosity remains same which is not really a true assumption, but density decreases very fast and therefore, the Reynold number changes. So, your C l C d will also expected to change. So, when we are talking about aerofoil I was mentioning that there a database knock aerofoil and if you Google for knock aerofoil 6 series or a 4 series you will find C l versus C d blocks are given in one of the assignments or you know one of the tutorial we will be presenting those, but each such values are mentioned pertaining to particular Reynolds number right.

So, when you are designing or selecting such aerofoil make sure that the aerofoil which you are selecting is good enough for the Reynold number it is closer to your main design altitude and design crew speed conditions. This I thought we must mention because if there is a change in Reynolds number substantially at a particular point about the cutoff point, the flow characteristic may change all your C l estimates may change for example, if you are thinking of designing a laminar aerofoil or a wing with the laminar aerofoil if there is a dirt or some manufacturing defect on the wing surface, the flow may become turbulent.

But in this case please understand the Reynold number if you calculate by this will remain same, but because of that or because of some imperfections locally flow may become turbulent or think of the situation when it is passing through a rain, most likely the flow will become turbulent. So, when I am talking about Reynolds number one is based on this, at the same time if you also look for cutoff Reynold number which are can be estimated based on surface finish. So, all those examples will be doing, but in a nutshell at this stage you understand that yes I need to ask myself what is the Reynold number I am going to fly for and accordingly I will select the aerofoil from the database this is very very important. Loosely you remember around Reynold number 10 to the power 5 around this these transition of boundary layer happens that is from laminar to turbulent these things will happen.

And most of the airplane they fly the wing will have 10 million value of Reynolds number a typical number. So, it is almost like in the turbulent zone, and not very far off from laminar unless and until you design something which I we call a laminar aerofoil. So, ensure that the Reynolds number is satisfying the condition of Reynold number to be a laminar to ensure laminar flow. All those details we will be talking as we go explicitly in the design with case studies right.

One problem you face in this design clause is we need lot of database to be used. So, my advice to all of you would be either you Google it or textbook many design books are there I am following Ramer at this point, if you are a really good designer or you want to become a good designer you want to really enjoy this course, get one book Ramer’s book or the act of design you will find one 2 one correspondence at its initial part of it right. As soon as I will be changing the text book or any material I will be mentioning you so that you can have a cross verification and once you read you learn more than you listen to a lecture right.

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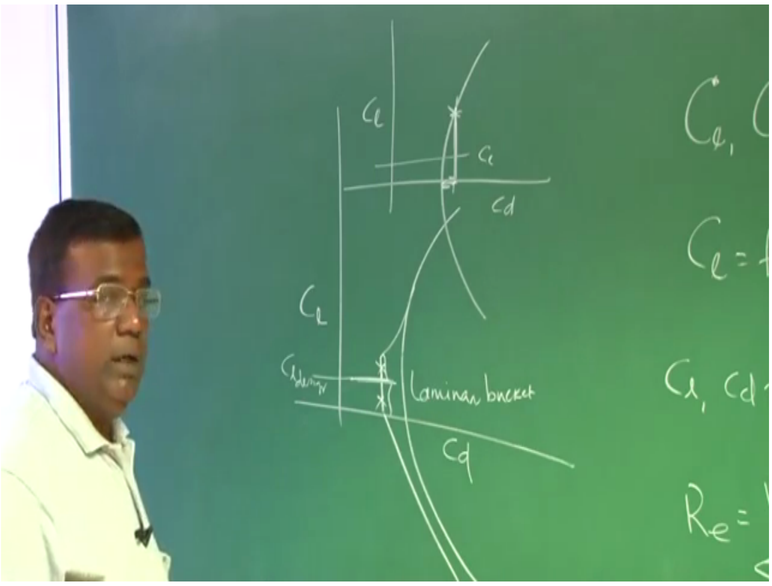

When I was talking about laminar you know 6 series aerofoil were primarily motivated because of this laminar bucket, this is the laminar bucket and the reason is that if we design the airplane for a particular C l let us so this is the C l design whether you are here or a here there is no substantial increase in the C d of the aerofoil. So, you are flying more efficiently if I check with this sort of aerofoil 4 series aerofoil, if I am flying here at this C l if you want to fly at this C l this is C l and C d to see immediately there is a increment in the drag function right. So, that may not be very appropriate way of optimizing aerodynamic efficiency right.

So, that is why this sort of a laminar bucket driven aerofoil which is a 6 series onwards that become popular, but as I am repeatedly telling you laminar bucket have this things very easier to say or theoretically advocate, but from manufacturing point of view from the maintenance point of view one needs to be very very careful. You may ask if I will design an airplane I need to have gates for some numbers, what C l should I design the airplane for. Typically transport airplane C l 0.3 to 0.5 is a good gauge number right that will help in getting the initial aerofoil the finer things you can do as the design evolves, at this stage we are talking about conceptual design right.

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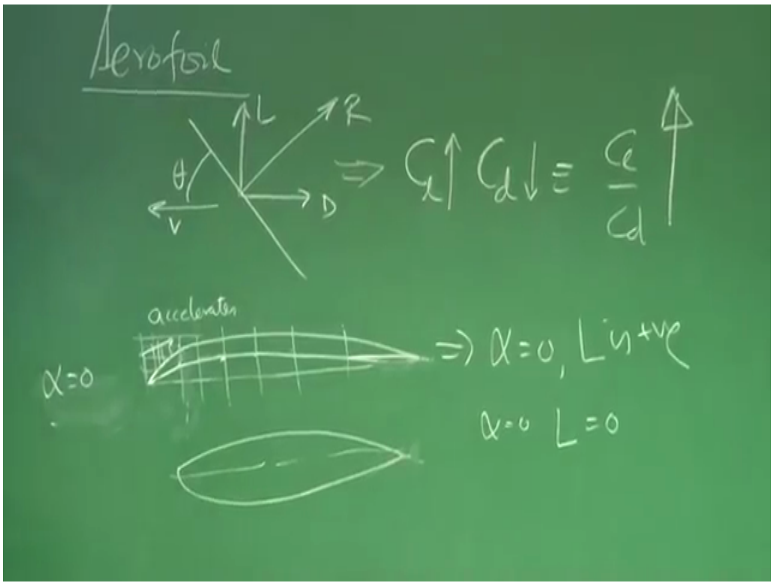

Again if I see what is finally, is an aerofoil we know that if a flat plate is moved with a speed v and if this angle is theta, this will produce a resistance R which one component we say lift one component we say drive. Why not a wing is just made up of flat plate why do you want so many things aerofoil and all. The primary reason for graduating from here to here is increase C l I want, I want drag or C d not drag C d to be low or in turn I want C l by C d to be higher that is the primary objective right.

Let us see suppose I have got a shape something like this symmetry; what happens alpha equal to 0 the flow is coming like this, whatever be happened here same thing will happen here all your theories a flow accelerates a pressure drop same thing will happen here. So, net lift net C l is 0 at alpha equal to 0 very simple, but now if I just remove this part how the story changes. I have removed this part so, now I could see that as the flow goes this direction, the flow accelerates this you know as the area of the contour is decreasing the speed will increase as the speed increases the pressure the static pressure will fall and that will tell you differential pressure in this direction the upward direction which we call lift.

So, now what is the difference between this and the symmetric aerofoil which was full part of this? The difference is in this case at alpha equal to 0 is still there will be lift that is at that alpha equal to 0 lift is positive, but for symmetric which is just mirror image of this if at here as alpha equal to 0 l is 0; and this is the beginning of what we call the cambered aerofoil.

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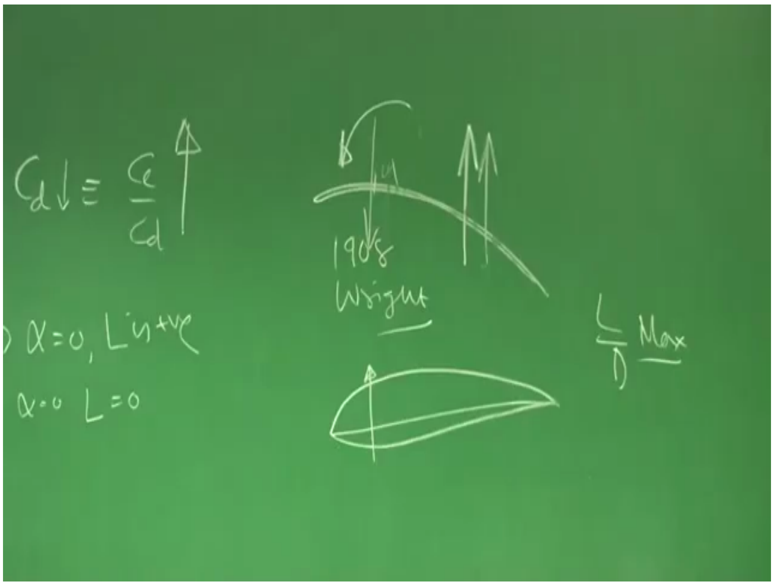

If I now see what type of aerofoil wright brothers said it was this and this this is this is the wright brother (Refer Time: 12:51) be only a cambered aerofoil and if I want to understand this via this what do I do, in our language we can draw mean camber line and the mean camber line will be something like this, and this is what is what here in 1908 is suppose wright brothers they used is a cambered aerofoil.

So, whatever cambered we are talking about imagine without any CFD without any high sophisticated tool this is purely analytical understanding and designer needs to encourage such thought process rather than getting lost into save the FEM all those tools. If you want to be good designer the basic level you try to understand finer things could be done offline, but thought process you have to look for the basic building blocks on which you can build your aircraft. So, I am just giving you example because this was important and this is important if you want to be a designer.

Now, is if with this logic if I want a shape like this, I also want I change the contour of top and contour of bottom if I make it like this again this will cause a differential pressure which will work upwards. Why there was a need for trying out different different contour? Because the focus was just not to get lift the focus was I want to have L by D maximum; because every lift will give a some drag I am talking about 2D aerofoil 2 d aerofoil you should not get mistaken if this 2 d simple 2 d aerofoil putting like 4 series not in laminar type.

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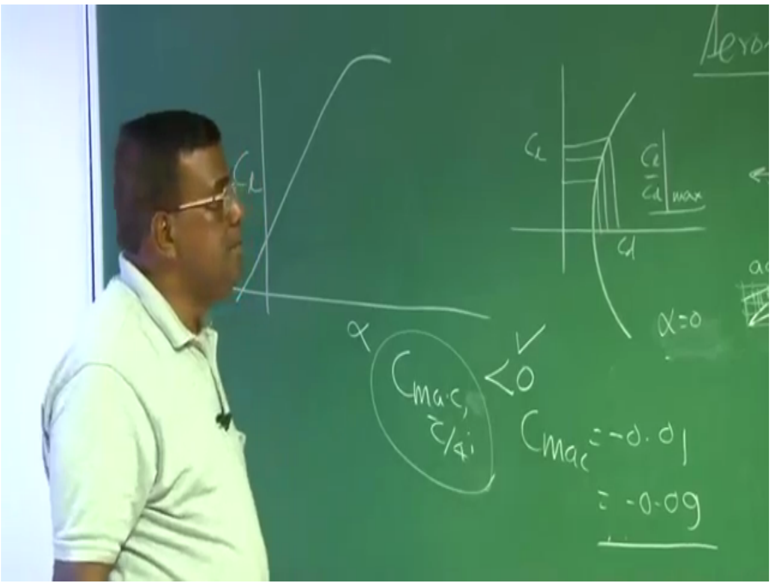

So, for every C l there is a C d and this C d is not induced drag because aerofoils are generated assuming infinite span and infinite span does not have any induced drag. These are because the flow separation that is as this gentleman angle of attack increases at some point flow will separate. So, this sort of a C d has constriction component as well as pressure drag because the flow separation. These are not vertex induced drag or induced drag. The question is at what point I get C l by C d maximum how do I ensure the contour of aerofoil so that C l by C d is maximum. Is the one aspects that is how you find different types contouring is coming.

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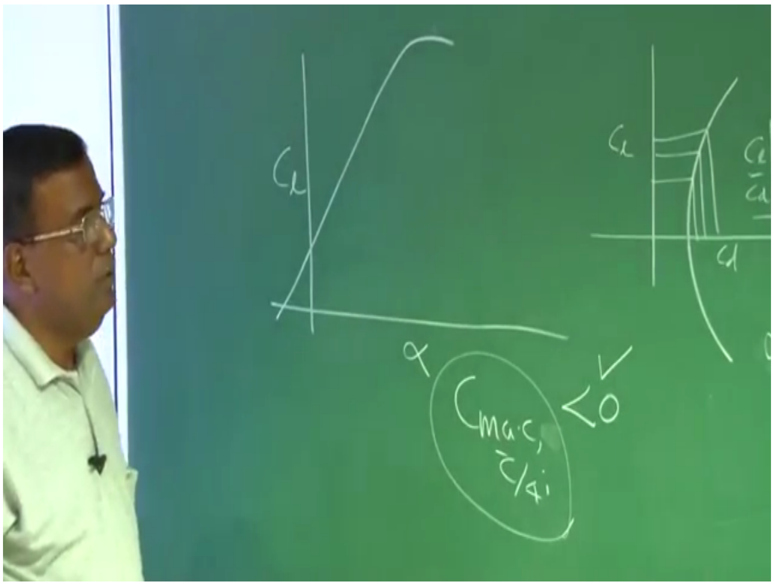

Second point came if at alpha equal to 0 if at alpha equal to 0 you want lift its a cambered aerofoil then you have a penalty called C m a c of the wing or aerofoil which will be less than 0. The C m a c I am talking about let us say about C by 4 of the aerofoil moment will have a reference point right.

Now, the point is what is the problem if C m a c is less than 0; this much you can understand as I am increasing the camber right then lot of force lower portion will generate the force which will give a moment negative at C by 4 which in turn means if there is a force here and force there when I am transferring this force from here to here I have to put a balancing moment which we call C m a c and you have been exposed to all this understanding in stability and control, as a designer I need to know how I am going to handle C m a c minus 0.01 and minus 0.9.

We will find as you are increasing camber for getting more and more C l machs, the C m a c is becoming more and more negative which is naturally true because this part goes on increasing. So, what is the implication of C m a c being large negative? See finally, what do you want then you want a aircraft to be balanced flying like this it should be balanced if it has more and more C m a c negative which will try to take the aircraft down I need to balance this moment through horizontal tail.

So, if C m a c is large generally then the tail size horizontal size has to be increased to balance this moment or the arm has to be increased to balance this moment or the both the moment you increase the horizontal size means you are increasing the drag and the worth penalty, you will see as we progress also that there is a way of doing a trade off by playing around with the a c of the wing, but in general if C m a c goes on increasing in negative direction, the effort additional effort we expect from the horizontal tail hence the size will increase or the momentum is size of the airplane fuse large will increase which is not all the time encouraged.

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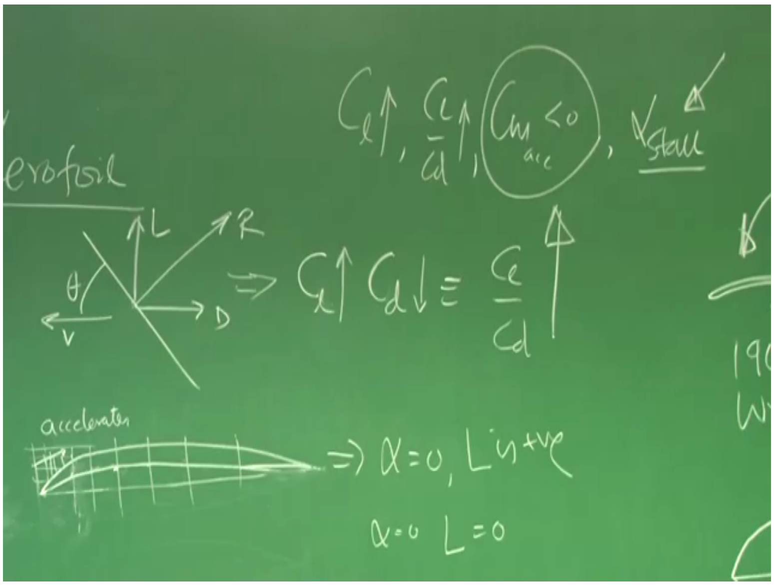

So, when you are talking about cambered aerofoil, one thing we realize we are looking for C l to be higher we look for C L by C d to be higher, we want C m a c less than 0 I want to handle it properly I have to keep it in balance; is a another important thing which comes the stall angle. More and more cambering you are doing in your airplane wing or in the aerofoil the C l max you may get more, but at the cost of alpha stall becoming lesser or lesser right this is a natural trend you have to careful about alpha stall as well.

The whole evolution of aerofoil has come up aerodynamically to ensure that after handling all these conditions we have an aerofoil which optimally satisfies all these 4 constraints right. In that direction if you see when I am talking about this in general I am mentally I have focus for a low speed airplane design right, but as you know mankind want speed from low subsonic to subsonic subsonic to supersonic or transonic supersonic hypersonic, so many way the ladder is being challenged accordingly you will find the wing or the aerofoil shape also will change. We will have separate session for high speed transliterations I am add this point talking about low speeds so that basic thing you understand and you can go on adding features as we increase the speed regime.

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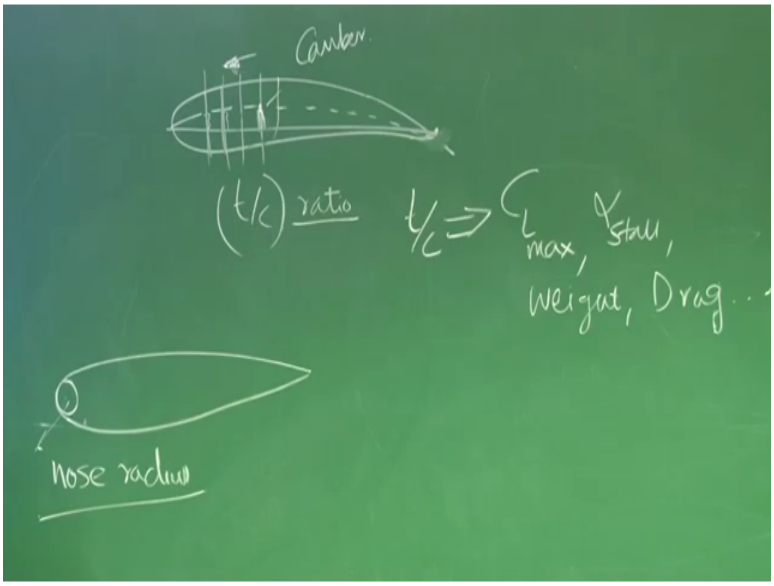

When we are talking about aerofoil so, I draw the aerofoil one words to say the camber line or the camber right and you know if I draw this curved line then draw perpendicular to the card and this distance is the camber. If it was symmetric the card and the cambered line would have been in same or coincident to say camber is 0.

We also know that there is a special significance for the maximum camber the location of maximum camber. Why that is important if location of maximum camber is this side; that means, we also have notice that camber line makes an important contribution to the whole new distribution and the location of maximum camber plays an important role for a particular design you may like this location of maximum camber to be in front we want a rise in the C l max. You may like to distribute the location of maximum camber depending upon overall pressure distribution over the wing, which will guarantee aerodynamic efficiency.

So, we play around with the location of maximum camber that is when aerofoil nomenclature you find there is a description where you know maximum camber is located at 0.4 c or something like that. Another important thing what we have noticed is this thickness to card ratio this is very very important; from designers why should a designer want a t by c ratio higher general feeling if somebody said I want a high t by c ratio. Immediately you know that he is trying to get larger volume and he want to accommodate in at the fuel time or some other sub subsystems inside the wing, but the moment you say t by c ratio is higher the aerodynamics you say on hold on it has some implications.

So, let us see how t by c plays an important role and what designers should be aware of. You know why now this is we call we are talking about nose speed nose radius right there is a general understanding that t by c will affect C L max, stall alpha stall, weight, drag etcetera.

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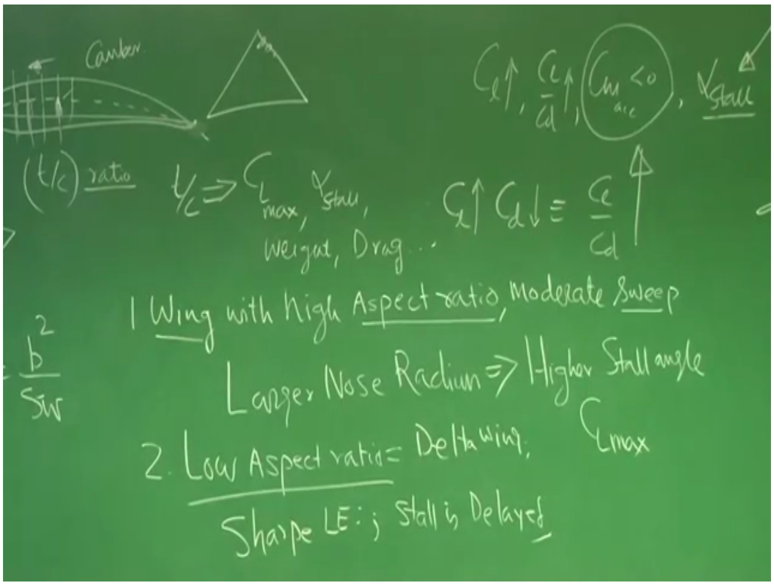

But if a designer wants to share some of his feeling he will say wing this is very important wing with high aspect ratio moderate sweep larger nose radius results in higher stall angle and C l max. please understand this is a statement for low speed where the catchword is wing so far we are talking about aerofoil now, suddenly we have jumped into wing we have also mentioned a word called aspect ratio and sweep. I have presuming that you have exposure to all these terms because you have done those courses just to make you comfortable the wing means the wing with different aerofoil or same aerofoil right.

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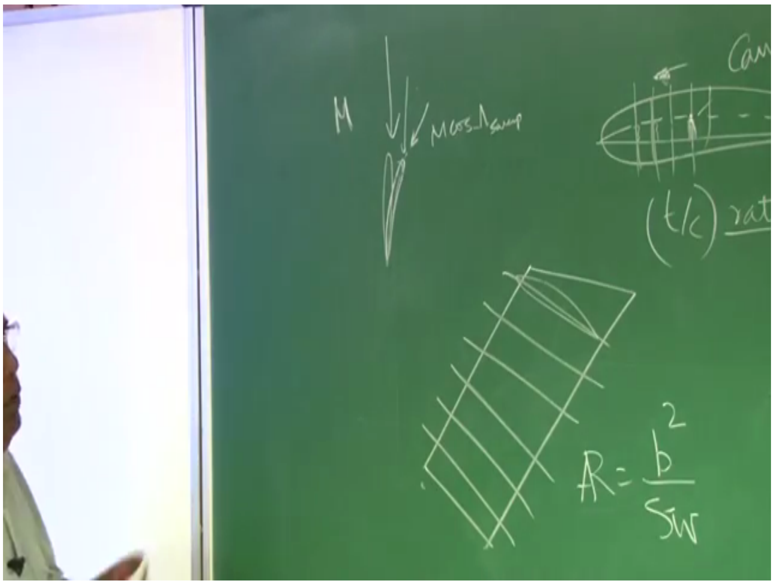

Aspect ratio of when you say this is band squared by the area of the wing, and sweep also you know of this is the aerofoil and flows like this, if I drag my aerofoil like this then there is a component which is M cos of sweep angle.

This is important that now the normal component is not M or what is mach number or it is the M cos of sweep angle that is normal component you know those sweep and we what we are talking about a moderate sweep mean 15 degrees, 30 degrees sweep high aspect ratio means what more than 8. If that is a combination of an aircraft for low speed then invariably you are likely to assume that if I put a larger nose radius I will get higher stall angle and C l max right, but the moment I talk about low aspect ratio.

Let us say typical example I am giving delta wing the story is different. These are all I am sharing feeling of an designer which he will a simply share at you without much of algorithm right. For low aspect ratio delta wing we will find we need sharper leading edge because their live generation is through vertices generated on delta wing, the vertices generated here through sharper leading edges recommended; as well as you know that for delta wing stall is very much delayed if you see the wind tunnel data if I am stalling almost not stalling type ok.

So, if you are designing a high aspect ratio moderate sweep then you know larger nose radius plays an important role in terms of stall angle is concerned C l max is concerned and the moment you are working for a low aspect ratio typically it is a delta wing type you need to look for sharp leading edge and stall is delayed far far delayed. This sort of a feel for configuration you need to have when you are designing something because when you are doing synthesis, you do not ask too many questions right you are an artist that time. So, you should select right type of candidate to stage a real performance.

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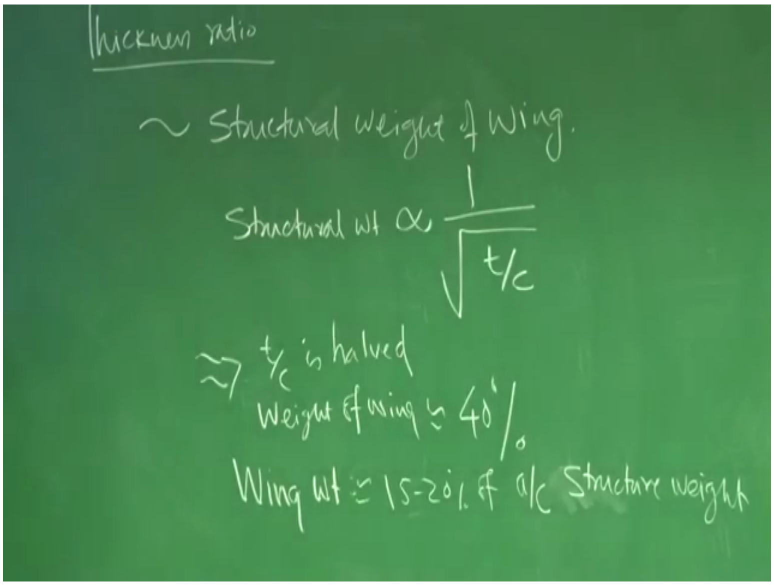

The another important thing thickness ratio it has direct application on structural weight of wing. Typically it is found that the structural weight the wing that is more important varies inversely t by c techniques to cord ratio. If t by c is large then you expect structural weight of the wing will also be reduce proportionate to these rough relationship which in for developing a feel you could see if t by c is half that means, the weight of wing almost reduces by 40 percent from this relationship and typically wing weight these numbers are important to start a design wing weight is typically 15 to 20 percent of aircraft gross weight or aircraft structure weight not gross structure weight.

So, you could see that if there is a reduction in 40 percent the weight of the wing because I have reduced t by c.

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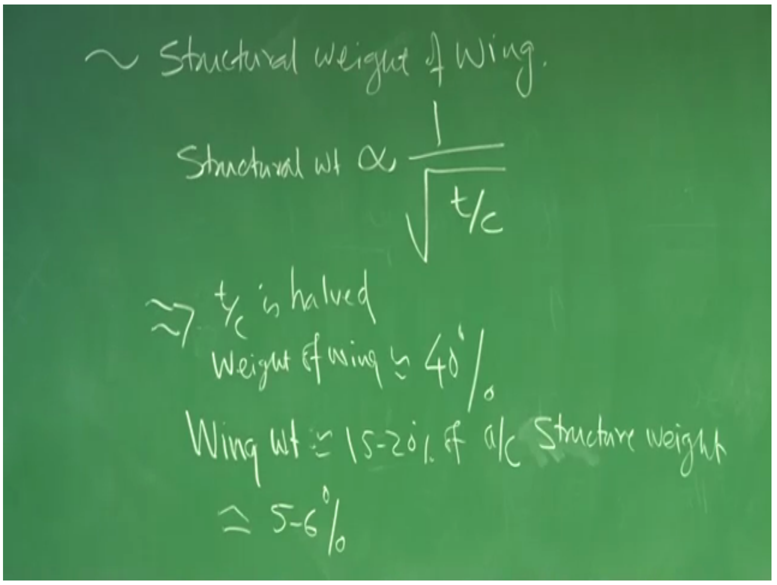

So, effectively overall aircraft weight will get reduced by 5 to 6 percent. These are these numbers I am putting so that you also get a feel if I do this how much I will get reduction and that is the tool of a good designer ok.

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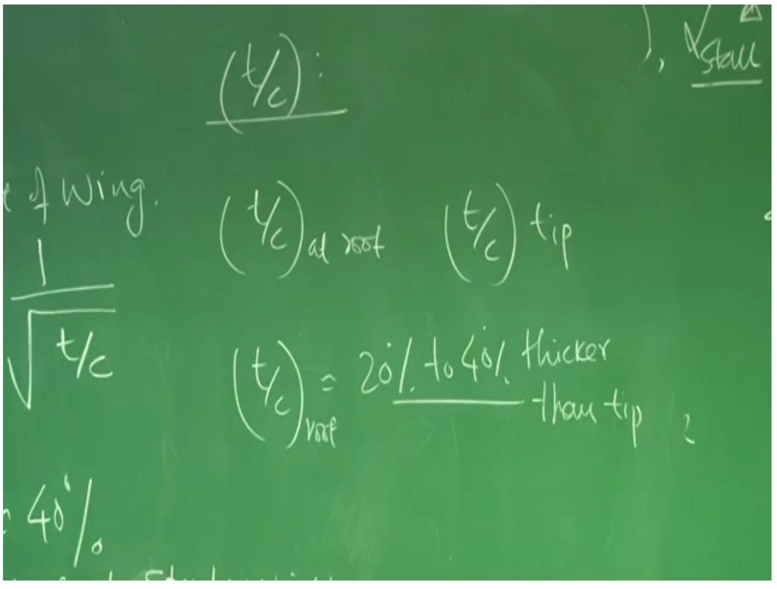

Since we are talking about t by c another observation you must have that t by c at the root and t by c at the tip they are different structurally the answer is obvious because maximum bending moment is at the root. So, why not you have more of stiffness at the root and in the tip the moment reduces. So, why do you want so much of area.

And typical number I can tell you that t by c at the root could be anywhere between 20 percent to 40 percent thicker than tip the last number. Please understand why I am mentioning this. So, in many many researcher or many designer will tell me why 40 percent it could be 60 percent. So, these are typical number as a smart designer you understand oh man this much is available make this much of volume is available with you can dump your fuel time from other accessories in that space of the wing.

And also there is an important thing is you see you see if t by c at the root is higher compared to t by c at the tip; that means, if t by c is higher it means this portion will try to stall earlier than this portion and my (Refer Time: 34:09) is tetra is here. So, root will stall first the moment root stall first why root stall first because t by c is higher at root stall first it will immediately create vibrations at the tail plane horizontal tail plane, pilot will be knowing that we are nearing stall conditions. So, these are all secondary effects the story began because the bending moment at the root is more finding more area right. The secondary effect is smart designer is good I will use that volume for putting my or installing my fuel time the airplane, the aero dynamics the flight mechanism as you find this will help me in getting a pre warning for stall right.

So, that is how I always say for a designer you need not be only bright you have to be smart also. There will be conflict, but the smart designer uses all these conflict for a natural conclusion making the airplane more efficient.

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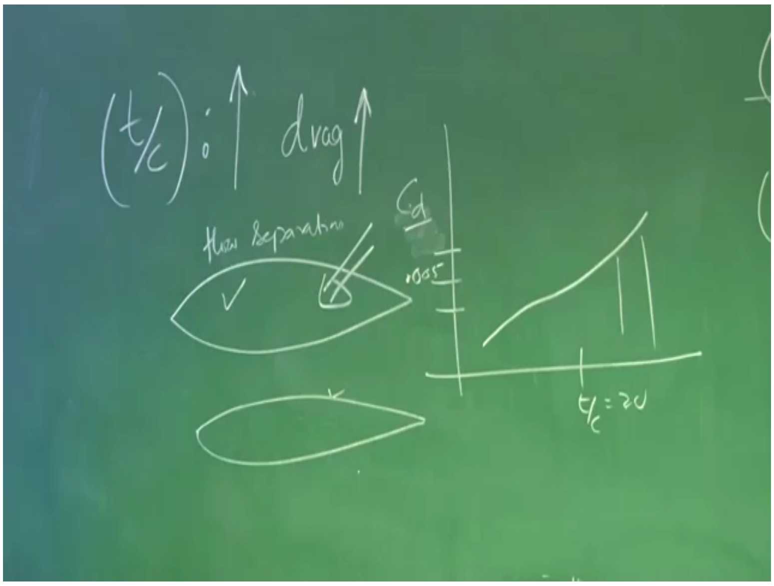

This t by c by now you will agree with me without much of a justification, if I increase t by c the drag coefficient the drag will also increase; obviously, if t by c is more you are disturbing larger amount of fluid outside. So, the drag also will increase and if t by c is more if compared with this and compared if you compared to this 2 thing is obvious that flow as far as separation is concerned will be predominant here compared to this to be earlier separation compared to this.

So, there is a drag changes and typically we find that t by c you can see the charts again you have to see the book this is your C d let us say 0.05, this is something it goes like this. As you increase t by c more than 20 the drag penalty is pretty high. So, everybody talks about 12 to 14 percent and that is where you talk about fat aerofoil or thinner aerofoil right. Please understand if I require larger t by c if flow separation is the only issue I could have handled flow separation by artificially injecting fluid at some point, but when I am talking about the whole design I am looking into what is the optimal way of handling it right that is why I need to know each element what are their limits, what happens if something goes beyond a particular number. Because more and more you talk about stall you cannot avoid talking about stall when you talk about t by c or an aerofoil.

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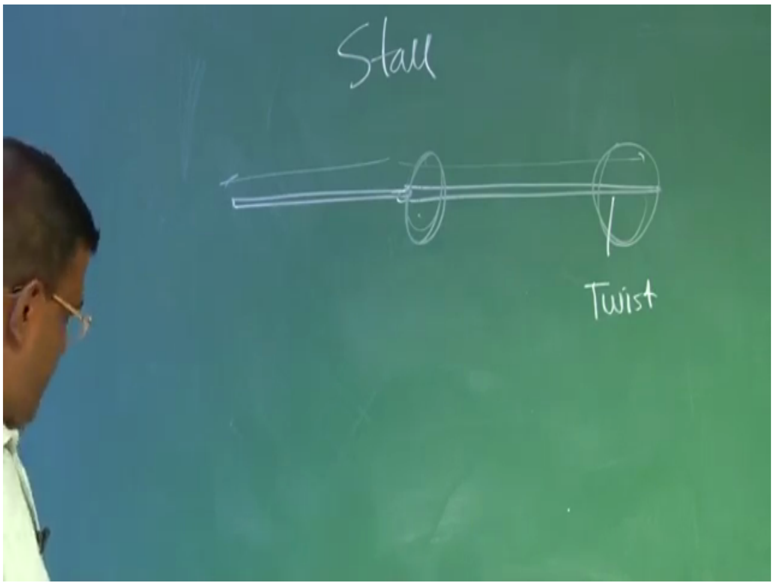

If I am talking about stall I am talking about wing if I have same aerofoil throughout this is same aerofoil throughout and I want that this portion should stall earlier than this portion, I am assuming even t by c is same right. Then the best way to ensure that happens is you give twist here twist this wing that is you take the wing here you give a negative twist that is here the aerofoils are like this. So, that even if here and the root 12 degree is there here 12 minus the twist angle.

So, again flow will separate first near the root then at the tip typically aeromonas language they call it wash out or the olden days they used to call wash out this is the another way of handling the stall I thought I must mention after that is another important thing we should revise.

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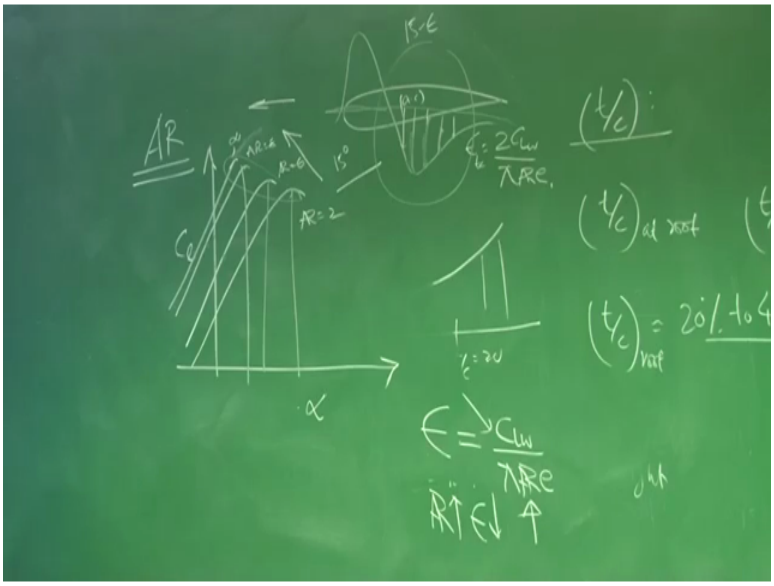

Since we are graduating from aerofoil to wing and that is aspect ratio right and if we recall our studies (Refer Time:39:06) performance goes, to find that this is aspect ratio some number I am giving it is a aspect ratio 6, this is aspect ratio 8 and close by it will be aspect ratio infinity.

Few things you should notice as a designer; do not think this lines as parallel observe only this point what I am trying to suggest as aspect ratio is increasing in this direction the stall angle these are a stall angle that is decreasing right. You know because the downwash gets its wing downwash it is C l the wing by pi aspect ratio. So, as aspect ratio increases the downwash at the wing will also decrease that is as aspect ratio of the wing increases epsilon will decrease what is this epsilon is it is not absolute at the tail please understand this. So, remember there will be up wash and there will be a downwash right; and we also know that the downwash at a c because this is a c, this is even by C l wing by pi aspect ratio e and downwash at tail is twice of that 2 C L wing by pi aspect ratio e.

Focus on a aspect ratio what is the message it tells that, if the aspect ratio of the wing is increased then this contribution will go on decreasing; that means, earlier what was happening if this is say 15 degree typically at that angle to wing stalls, because of this downwash this portion will be seeing 15 minus epsilon.

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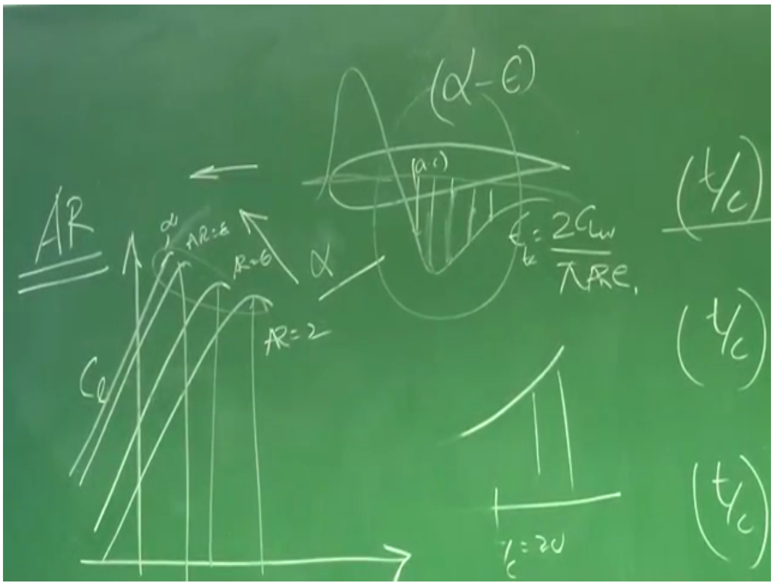

So, it will not stall it may stall a at our 17 degree. What do we say if aspect ratio is large the epsilon will be small, so it will have lesser stalling angle, but if aspect ratio is small epsilon will be large. So, the stall angle will increase and that is exactly happening as aspect ratio increasing the stall angle is decreasing right.

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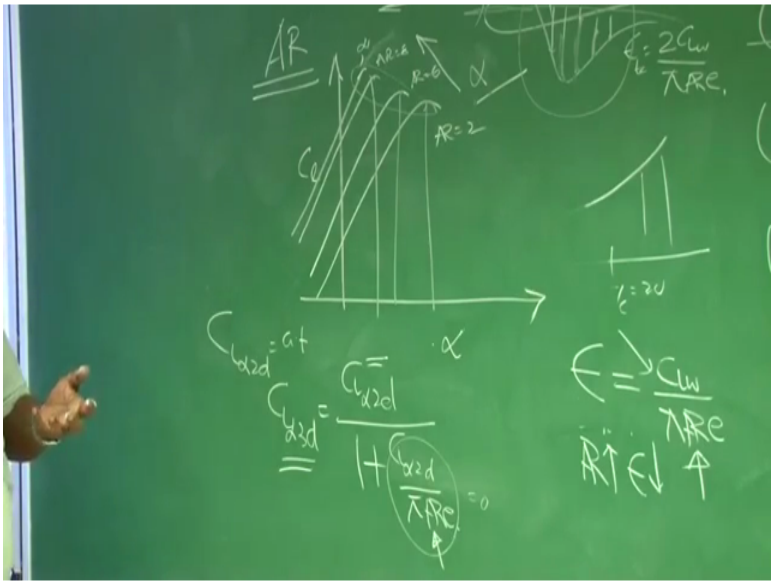

You also know that if I have C l alpha 2 d for an aerofoil, I know C l alpha 3 d I can easily compute using C l alpha 2 d by 1 plus C l alpha 2 d by pi aspect ratio e. Designer should get a field from here beyond aspect ratio 8 change in C l alpha is not much see what is happening if aspect ratio is large epsilon is less that means, it is actually seeing a lot the angle of attack because the angle of attack seen by this portion if they say some angle let us say this man was coming with alpha, because of this epsilon actually this portion is seeing alpha minus epsilon.

The force experienced by this wing will be proportional to this angle not this angle because there is a down washer. So, if this man is less then the lift force will be more, this man is less when aspect ratio is large. So, indirectly what I am getting a relationship as aspect ratio increases C l alpha also will increase which is seen here. If aspect ratio reduces when aspect ratio becomes infinity this gentleman becomes 0. So, C l alpha 3 d becomes C l alpha 2 d and C l alpha 2 d is the maximum value can have.

So, as aspect ratio is increasing slope will actually increase, but beyond the aspect ratio 8 there is hardly any change in the C l alpha of the wing. So, as a designer why do I say.

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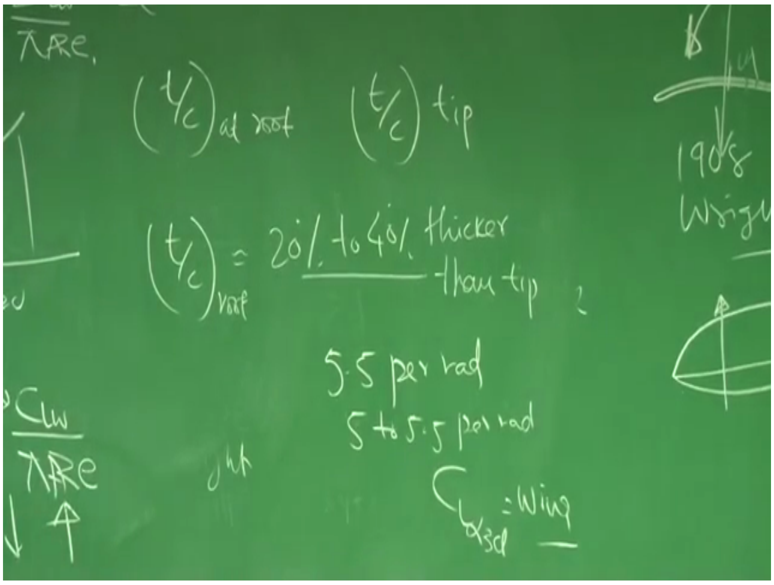

I say come on to initially I take 5.5 per radian or 5 to 5.5 per radian as C l alpha 3 d of the wing. I start making some approximate calculations, but when I write this I am clear that aspect ratio is more than 8 or around 8 these are all designers feel ok.

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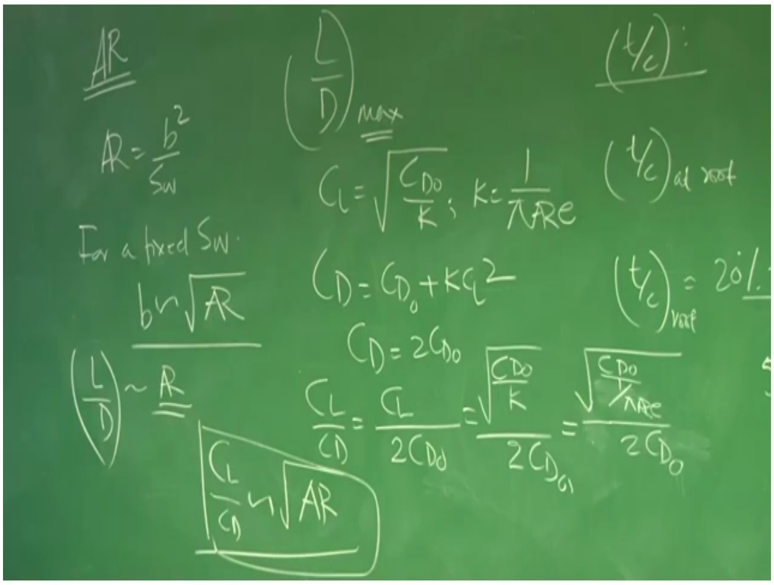

There is a another designers perspective with the aspect ratio we know aspect ratio is described by a s wing you might have decided wing area based on other considerations that is for a designer for a fixed S w, b is directly proportional to square root of aspect ratio. This is another very very important relationship which helps in this designer to get its initial field for numbers. Also one would like to know how L by D gets affected via aspect ratio why it is important. If there is a aspect ratio if I increase aspect ratio the induced drag part will go on reducing as induce drag goes on reducing the drag part will also goes on reducing and because of down wash there is an effect on the C l alpha you have seen.

So, how do I perceive L by D via aspect ratio that is also an important designers feel you need to have let us see that. You know we will talk about L by D max that is what a designer look for L by D max means C l is C D naught by K and you also know K is 1 by pi aspect ratio e and these are all on your fingertips, and C D equal to C D naught plus K C l square, C L equal to C D naught by K for L by D max. So, C d becomes 2 C d naught. So, what is C L by C D? C L by C D will be C L divided by C D which is 2 C D naught which is C l nothing, but under root C D naught by K by 2 C D naught and K is 1 by pi aspect ratio e if I further do this I get this is C D naught by pi aspect ratio by K right. So, K is 1 by; 1by pi aspect ratio e divided by 2 C D naught C D naught.

So, this sort of relationship come and from here you find C l by C D will varying with square root of aspect ratio this see here C D naught by K, K is 1 by pi aspect ratio e. So, C D naught by 1 by pi aspect ratio e. So, the pi aspect ratio will come on the numerator and C D naught is here this is under root of course, this is this under root do not you are smart you can do this please understand what I am trying to tell you is C L by C D will be directly proportional to the aspect ratio because this gentleman will come in the numerator because there is 1 by pi aspect ratio e.

So, the message for a designer is C L by C D will vary with square root of aspect ratio. So, if I am increasing the aspect ratio I know at what rate I can expect C L by C D will increase if you also have the very important understanding for a designer. As I told you earlier also whatever we have studied in performance flows or stability in control course I will try to present synthesize those things from designers perspective, that is why I give this number and we are interpreting in a little different way.