UAV Design - Part II
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Lecture-20
Weight Estimation and wing Sizing with Example

Hello everyone, I am Qazi Salahudden TA of the present course; the course name is UAV design part 2. So, today I will discuss some example problem suppose if you have any machine requirement, if anybody gives you the machine requirement and based on the given requirement, how will you design the aircraft or UAV?. So, let us say we have the machine requirements which are following like.

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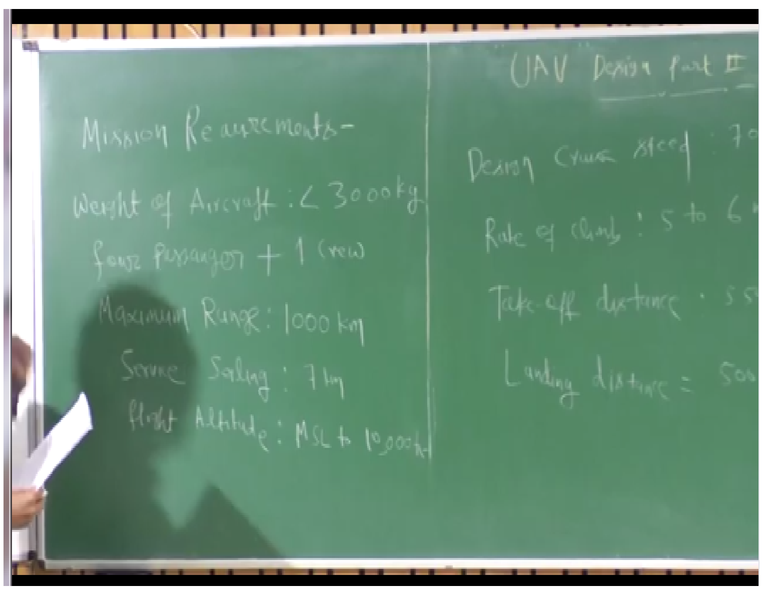

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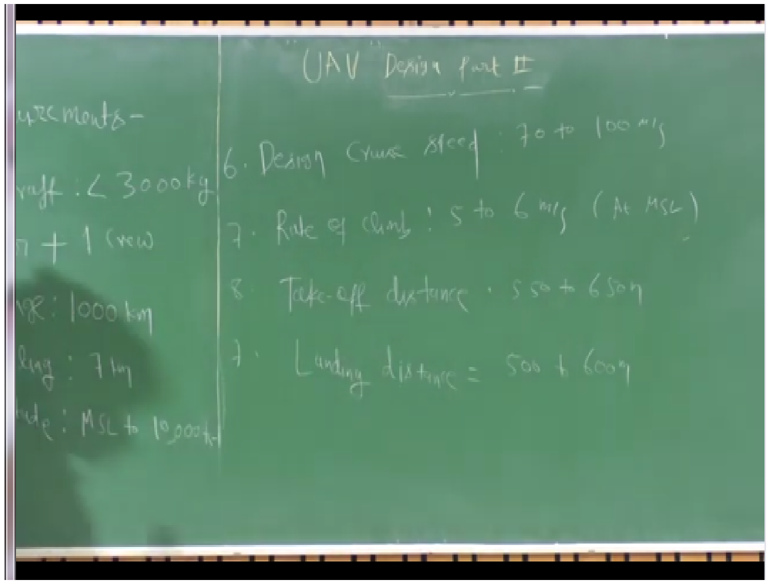

So, we have the following mission requirement like weight of the aircraft should be less than 3000 kg, this is the first requirement 4 passenger + 1 crew. Like here we are designing the manned aircraft, see suppose that we remove the person from the aircraft then it become the payload. So, you can consider this is a weight of the payload also, so from this mission requirement you can design the mined aircraft as well as unmanned aircraft also.

So, the third requirement is the maximum range. Our aircraft should cover the 1000 kilometer range at least and service sealing should be the 7 kilometer like this is nothing but maximum altitude at which the aircraft can fly this is nothing but the service sealing. Slight altitude should vary between mean sea level to 10000 feet, like if you want to fly down 0 kilometer, 1 kilometer. So, our aircraft should not be feasible to fly only mean sea level, it should also fly at least from mean sea level to 10,000 feet, ok

6 requirement is designed cruise is speed should be in between 70 to 100 meter per second. Because here you are changing the altitude know, so your flight speed will also change. And the seventh required means is the rate of climb should be 5 to 6 per second this is also very important criteria for designing any aircraft. Because you want to climb as fast as possible or sometimes we want the aircraft to fly as low as possible like based on the mission requirement, the rate of climb is a very important criteria.

And the eighth one is takeoff distance should be 550 to 650 and seventh one is landing distance should be in between 500 to 600 meter. Because these are also the restrictions sometimes the runway or shorter sometime we have more like longer runway these 2 will also come ok. So, typically we will see how the mission profile will look like?

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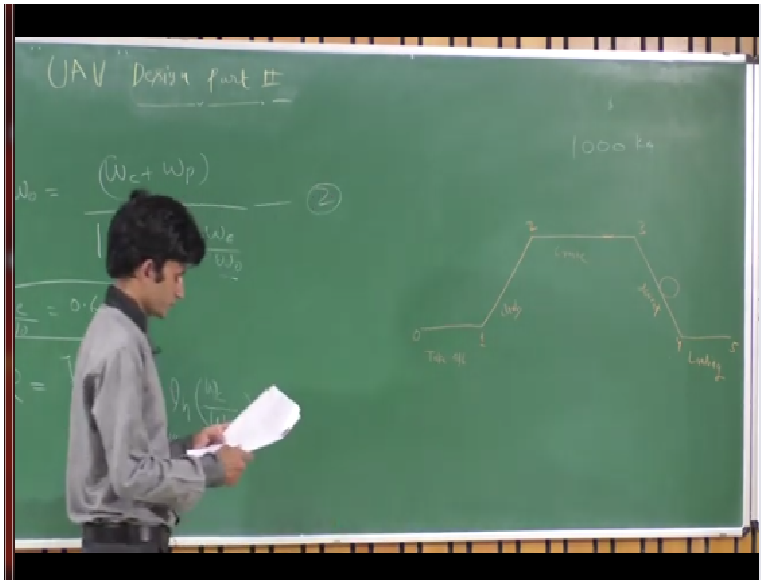

So, as you can see you will start from here, suppose that you are starting from here you mark as a 0 and then you are basically taxing ok and then you are going to climb and then there will be the cruise and then descent. Here you can also later (()) (06:47) and then you will land your aircraft ok. So, basically you mark 0, 1 then 2 here and 3 here suppose there you are not (()) (07:06) here your (()) (07:07) point is here only.

So, this is 3 and this is 4 and this is 5. So, this is nothing but the takeoff phase, this is your takeoff phase, this is your climb phase and this is your cruise phase and this is your descent and then finally you will land your aircraft ok. So, now if your aircraft is fuel powered, you are taxing from 0 to 1 then taking off and climbing from 1 to 2 then cruising from 2 to 3 and then descending from 3 to 4 and finally landing from 4 to 5.

So, continuously the fuel will consume, so your aircraft weight will not remain the constant, ok. So, in our design example first we will estimate the weight of the aircraft like what should be the weight of aircraft? In order to achieve this requirement, so let us see how to estimate the weight of the aircraft. So, first we will define what are the different types of weight aircraft has like?

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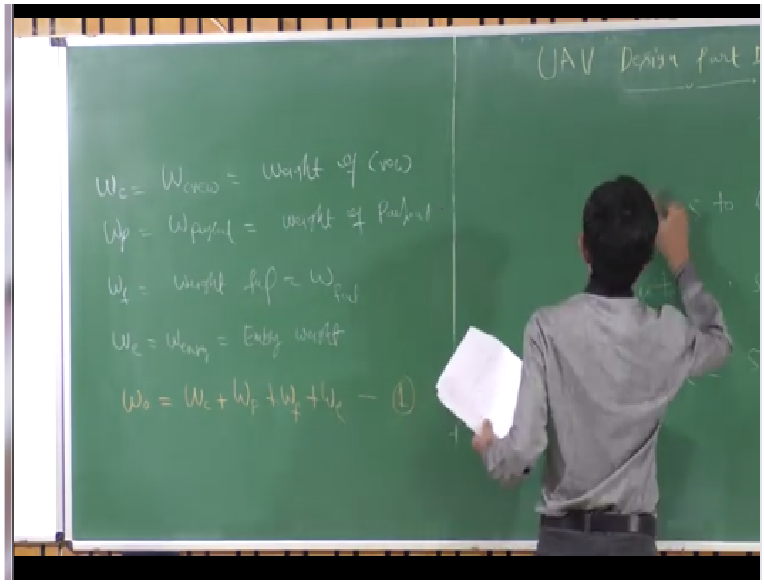

First weight will be the W crew the weight of the crew member, ok. So, short form is W c, W crew equal to weight of crew, W p is weight of the payload, W f is weight of fuel is also we can W fuel, W e is an empty weight W empty weight of the aircraft. So, total weight of the aircraft you can write as W 0 is a total weight of the aircraft, then W 0 will become the sum of this weight, W c weight of the crew, W p weight of the payload, W f weight of the fuel and W e is a empty weight, you can take as a equation 1.

One thing you can notice in equation 1, you do not have any weight, right, you do not have W c, you do not have W p, you do not have W f, you do not have W e, what you will do here? So, if we do not know the individual weight we will find out the fraction weight, how we will see later?

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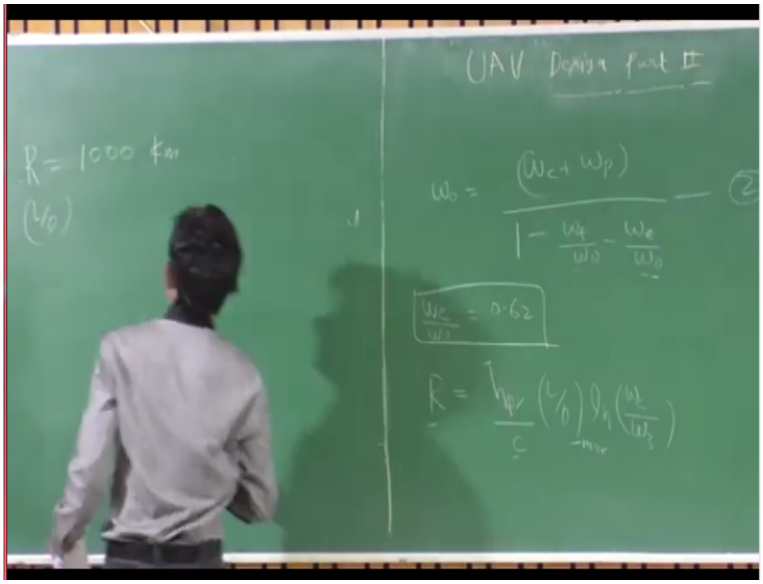

So, if you do some mathematical manipulation here then equation 1 can be rewritten as W c + W p divided by 1 - W f by W 0 - W c by W 0. If you bring this here and if you rearrange you will get equation 1, from equation 1 you are getting this you mark as a equation 2. So, now you can see equation 1 and you can see equation 2, equation 2 is nothing but written in terms of fraction like fraction with W 0, like W f by W 0, W c by W 0. So, this fraction we can find out like W f by W 0 we can find out. I will tell you how we can find out these things?

This is W e, empty weight, ok, not W c. So, when you are designing your aircraft you know the crew weight, right, and you know also the payload. So, if you know these 2 fractions W f by W 0 and W e by W 0, you can find out the value of total weight of takeoff, right. So, let us find out the W e by W 0, so as you know so many aircraft already has been designed, right, numerous number of aircraft has already been designed which lie on the category of the aircraft which we want to design like less than 3000 kg like.

So, if you do the latest survey then you will find out to based on the current weight requirement your W e by W 0 will come out around 0.62. You can follow one book which is aircraft design by D. P. Raymer it is a conceptual approach and another one is J.D Anderson aircraft performance and design. So, in that you can find out this value because I am taking from there only, ok.

So, W e by W 0 is 0.62, so many books are available to find out the W e by W 0 but I am giving the 2 reference first one is aircraft designed by D. P Raymer and the second one is J.D Anderson the book name is aircraft performance and design. So, W e by W 0 we have, so if we found out W f by W 0, we can get the W 0, so now we will find out W f by W 0, ok. You can notice that your aircraft is cruising from 2 to 3.

And you also have the range requirement, range requirement is what? It is maximum range should be 1000 kilometer, so 1000 kilometer you have range. So, based on this data range, you can find out the weight fraction from here to here, how will you find out? See if you already want to design the propel powered aircraft like generally it is category of aircraft lies will be the propel powered only not jet powered only, ok. So, you can write range of the propeller powered aircraft.

Propeller powered aircraft means the engine will be piston engine or a reciprocating engine and connected to the propeller, ok, eta pr by C L by D ln W 2 by W 3 is starting from W 2 and ending to W 3 in cruise phase, so W 2 by W 3, so this will be the range. So, you can notice that, if you know the range and if you know the engine specification like how much a specific fuel consumption the engine has and propeller efficiency?

And at what L by D you are flying? You can found out the W 2 by W 3, so in our case what is range? So, after this follow me here.

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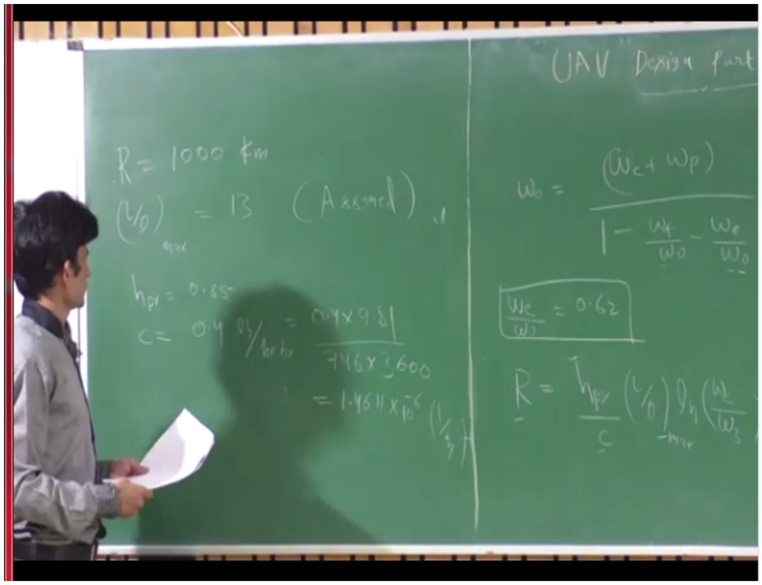

Like you have range 1000 kilometer, right, it is given 1000 kilometer range it is given, and L by D maximum range right. So, if you are flying the maximum range then L by D should be max ok. So, L by D max also given, let us say 13. If it is not given then assume, ok, see these are the iterative process, if your machine requirement does not satisfying you have to take the another loop eta pr 0.85 generally and C is once you select the reciprocating engine you will get their specific fuel consumption, generally it is 0.4 lb hp per hour.

So, you can notice that it is better to convert all the unit in a SI unit only, you just convert into the 1 unit I mean to say. So, like range is not given kilometer, convert into meter and these are lb hp hour, do you just convert into SI unit, what you will get? 0.4 lb is given know just multiply by 9.81 what is hp? If you 746 1 hp = 746 watt, ok. And then hour to second you just multiply by 3600, so you will get 1.4611 into 10 power - 6 1 by meter.

So, you can see this has no unit, this has no unit, this also has no unit, and this is 1 by meter, meter will go up you will get the range meter, ok. So, if you substitute these value, R value here also eta pr in c here, you will get W 2 by W 3.

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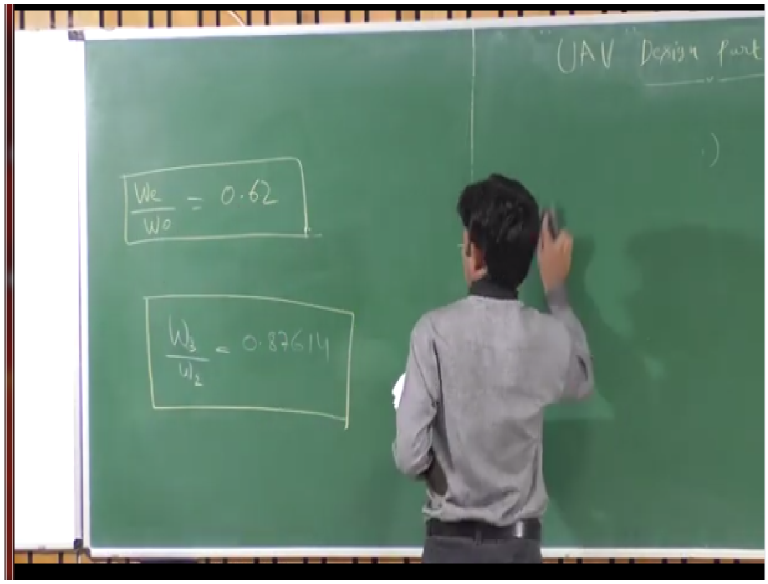

Range is 10 power 3 ok, then eta pr 0.85 what (()) (18:45) you got 1.4611 into 10 power - 6 ok, your L by D is 13, ok, ln W 2 by W 3. Solve this you will get W 2 by W 3 is 0.87614, see I request you to please take at least 5 digit, so that you can get the good results. If you approximate here means you are approximating here and if you are approximate here you will are approximating here.

So, everywhere if you do the approximation your result will not be correct, ok. So, you just take at least 5 digit, ok, if it is there. So, you are getting W 3 by W 2 sorry this is W 3 by W 2 W 2 by W 3 you will get 1.14136. If you reverse this W 3 by W 2 will come 0.87614, what will there like? W 4 by W 1 and W 4 by W 5 like what is the fuel consumption in descent phase? what will the fuel consumption in landing phase?

So, now from this data we can find out the how much fuel consumed in cruise phase, not descent phase, not landing phase, not climb phase not as well as takeoff phase. So, in this 4 phases 1, 2, 3, 4 we have to approximate and from the given data we can find out the amount of fuel consume in cruise. So, you just remember this W 3 by W 2, we will use this, ok, and W e by W 0 also W e by W 0 which is 0.62. Actually we did not get we have taken from the latest survey, this we got from the forum 0.62, ok. I will tell you what is the use of this?

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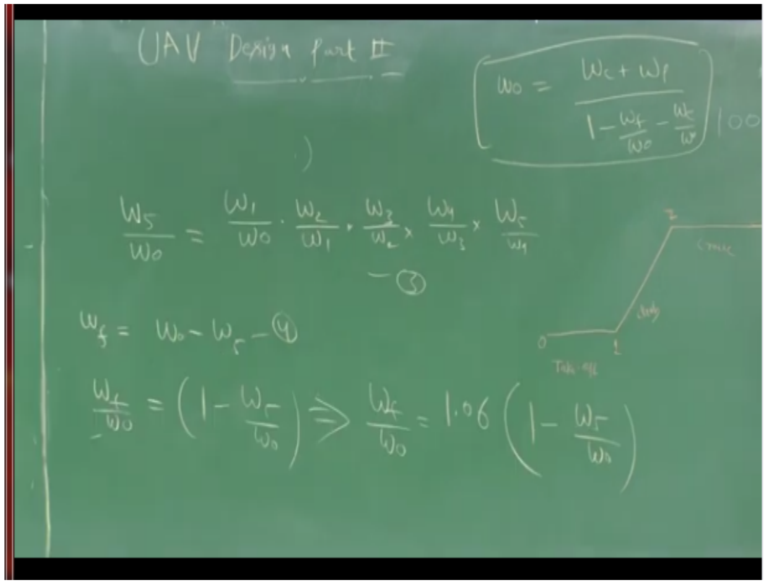

So, you just see from W 5 and W 0, you can write mathematically W 1 by W 0, W 2 by W 1, ok, then W 3 by W 2 multiply W 4 by W 3 and W 5 by W 4. See W 4, W 4 will cancel W 3, W 3 cancel W 2, W 2 cancel W 1, W 1 cancel you will get W **1** 5 W 1 which is written here. So, that means you can write W f by W 0 like this. So, why we are writing this? See if you closely see this expression W l by W 0 is a weight fraction from here to here.

Similarly this will be from this to this ok, likewise W 5 by W 4 is nothing but for landing ok and what will be the fuel weight? Like W f will be W 0 if you consume all the fuel you are starting from here and landing at this place and you are saying that all fuel you will get consumed. So, at the end what you will have? Here you have W 0 weight and here you have W 5 weight and your all the fuel get consumed, right.

So, you can write W f is nothing but W 0 - W 5, you just subtract this two, ok. Earlier we have make a question 1 out 2 know. So, you just make this 3 and 4 ok, you just do some mathematical manipulations, simple you will get W f by W 0 just divided by W 0 you will get 1- W 5 by W 0. Now if you say my fuel did not get completely consumed like 6% or 7% we have a saving then this expression you can further modified W f by W 0 = 1.06, that means 6% fuel you are reserving like see in your everywhere in your bike your car also the some fuel are reserved know.

So, in aircraft also some fuel is a reserve, let us say we 6% fuel are reserve, ok. So, these expressions will nothing but become W f by W 0, ok. So, you can slowly observe that what time doing these things like? If you go back to my when I started the lecture I written that W 0 = W c + W p 1 - W f by W 0 and W e by W 0, if I am not mistaken. To estimate the weight of the aircraft, so we do not have W f by W 0, will from literature survey we got W e by W 0.

But that time we do not have W f by W 0, so you can see now we are finding W f by W 0, ok. For that we need W f by W 0, and for this W f by W 0, W 5 by W 0 we are getting from equation 3. So, in order to find W f by W 0 we need W 1 by W 0, W 2 by W 1, W 3 by W 2, W 4 by W 3, W 5 by W 4, so W 3 by W 2 we have already found out, ok. So, now we want W 1 by W 0, W 2 by W 1, W 4 by W 3 and W 5 by W 4, ok.

So, every value is important and I need the place let us say 0.62, I am writing again. And 0.87614 this is W e by W 0 and W 3 by W 2, erase this we will get the space in order to do the further calculation.

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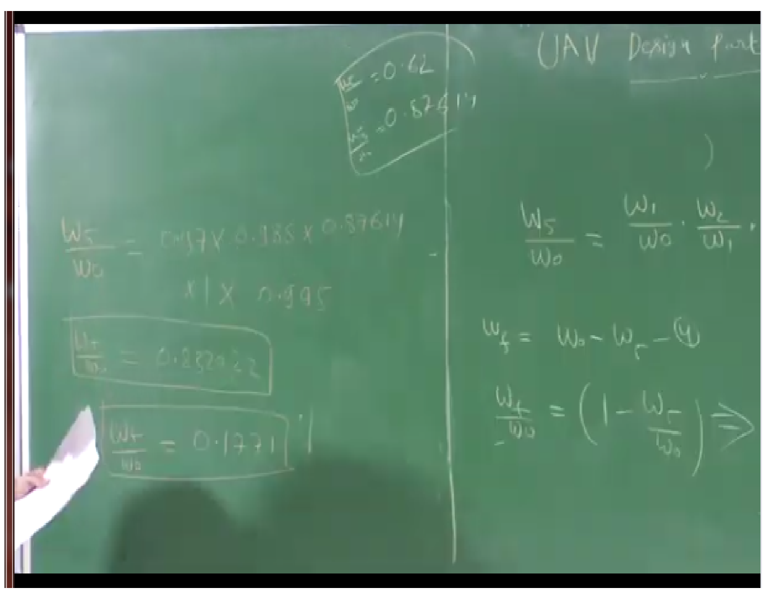

So, you just closely observe the equation 3, W 5 by W 0. So, W 1 is W 0 means from 0 to 1, so the ratio in literature survey you will get 0.97, for this weight category of aircraft. Similarly as you got here W e by W 0, ok, and W 2 by W 0 will be 0.985 ok, and W 2 by W 3 you already got the very correct value, ok. And then W 4 by W 3, so W 4 by W 3 means at descent you are not consuming any fuel.

In reality you will consume some fuel as of now you just consider 1, it negligible at exactly 1 and W f 5 by W 0 in landing 0.995. So, if you multiply you will get 0.832022, this will be the W f by W 0, if you put this W 5 by W 0 in the modified equation with 6% fuel reserved, W f by W 0 you will get, 0.177, you just also get some fuel for this fraction, like see the W f by W 0 is very less compared to these 2 fraction.

So, weight fuel fraction is less compared to the empty weight fraction and with respect to the total weight the fuel weight is very less. Like here do not compare this ratio with this, compare this ratio with this because this is written in the W 0, it is also written in W 0. So, empty weight is more compared to the fuel weight, ok. So, you know the fuel weight and you know the empty weight fraction you just put these two fractions you will get W 0.

But there is a way to put the find out the payload, how will you find the payload? Like we have already a specified the passenger way 4 passengers there, right, and you know if you are going for a flight you will also have some bags and all. So, that weight also will come into the picture, like at least 15 kg bag weight, ok. So, these two fraction is there, now we will write approximate here.

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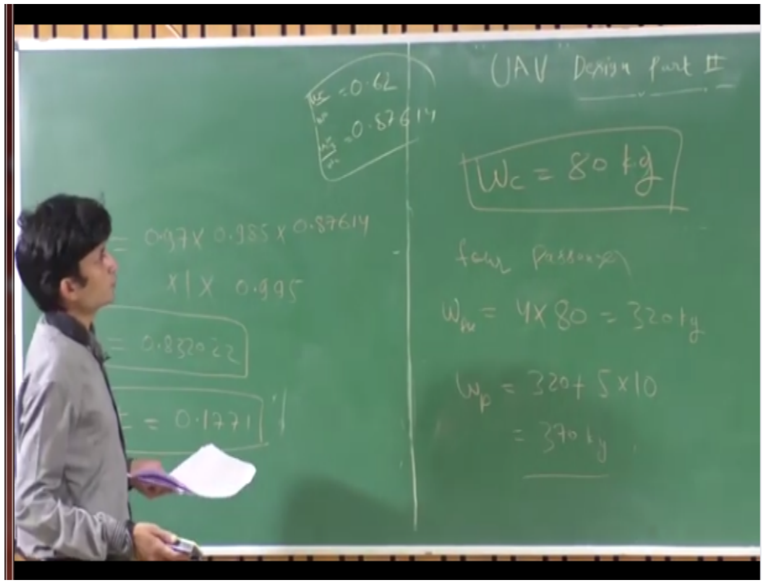

So, the average crew weight will be the 80 kg that is the normal 80 kg or 75 kg that is a normal average human weight, healthy human weight. So, we have 4 passenger, right, so the passenger weight will be W you just say passenger pas 4, 1% weight is 80, 4 into 80, this will be the 320 kg, ok. And let us say every person is carrying 10 kg extra weight, so how many person is there? 4 passengers + 1 crew, 5 man, right.

So, W payload will be nothing but 320 and 5 passenger carrying 10 kg extra weight which is nothing but the bags and all 5 into 10, ok, you will get 370 kg ok, this is nothing but your payload weight, ok. So, I think you got all these thing W c also fuel weight, W p also payload weight, W f by W 0 which is fuel fraction and W e by W 0 which is empty weight. So, you just substitute these value you will get the answer.

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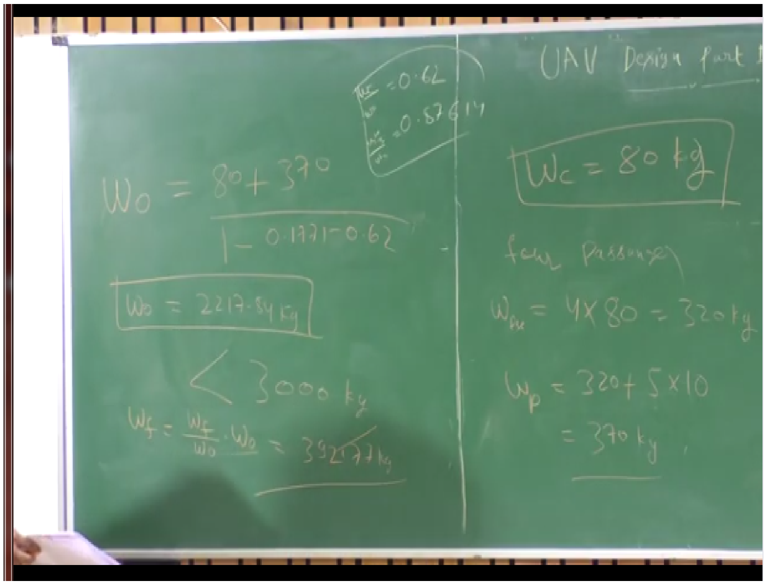

So, now I am estimating W 0, which is nothing but the weight of the aircraft is 80 kg already fixed, payload you have find out 370 kg, fuel weight 0.1771 - 0.62 is empty weight fraction, ok. You will get W 0 2217.84 kg which is nothing but less than the 3000 kg which is our requirement, ok. So, now you have W 0 right, additionally you can found out the W f also, how much amount of fuel is required in order to complete this mission? So, W f by W 0 into W 0 these faction you know, W 0 you know if you put this value you will get 392.77 kg, ok

So, your weight is estimated, remember that your weight is W 0 is 2217.84 kg, ok, I request you to do this exercise for a no passenger, no crew, just payload weight 100 kg that is it, that means unmanned aircraft right, this is the manned aircraft, you have passenger. So, I request you to do the exercise for a unmanned aircraft you will get the field. So, our weight is estimated, right, this weight, but your air craft is flying, how will you lift this weight?

This much weight 221784 kg you have to lift and you know aircraft wing can lift the whole aircraft, right, means 90% of the lift is coming from the wing. So, how long and how wide your wing should be in order to meet this requirement? Like lifting this much kg of the weight, so next we will see the wing design in order to for lifting the weight, ok. Mostly our aircraft is flies at a steady state level flight, like if you compare that time from 0 to 1, 1 to 2, 2 to 3, 3 to 4, 4 to 5 you will get your aircraft is mostly fly from 2 to 3, ok.

So, if you are aircraft is in mostly flight that particular condition then we have to take the consideration like we have to design our craft which is satisfying all the requirement in that phase 2 to 3. So, when your aircraft is flying at a steady state in level flight STD state and level flight means your wing is level. You are not rolling right and you are not rolling left your wing is level and you are maintaining the constant altitude.

You are not dropping altitude and you are not increasing the altitude and you are following the straight path. So, STD means with the time the variable is not changing to here the altitude is not changing with time, ok, the STD is a level flight.

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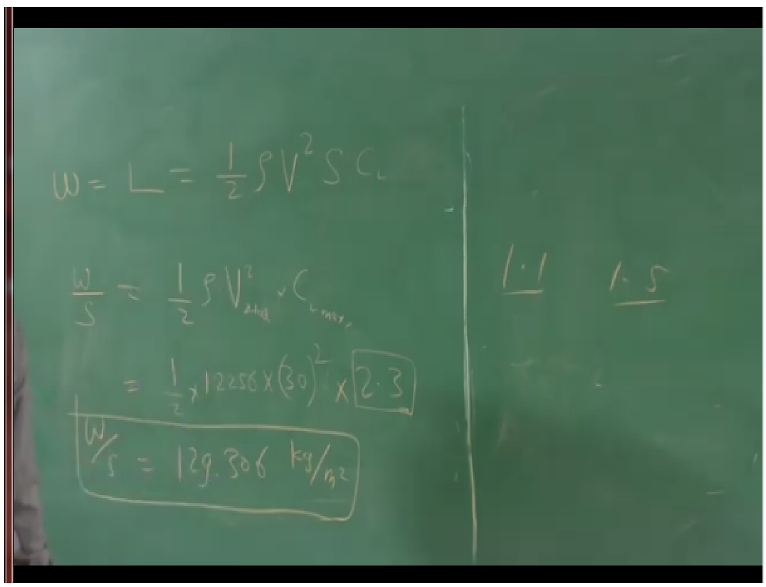

So, that means your weight or the aircraft should be balanced by lift and which is nothing but half rho V square S into C L this is your lift, ok. See there is a limit of V at which you can sustain the lift equal to weight. So, that minimum speed is called a stall speed and correspond to that minimum speed the C L will be the C L maximum, ok. You are flying at the maximum angle of attack at which it can sustain the steady state level flight.

So, now this expression will become W by S, bring the S here you will get 1 by rho V star square into C L max, ok. Sometimes these in a requirement is stall speed is also given like the stall speed should be minimum 30 meter per second like if it is saying. In the present case suppose that you are flying at a sea level, you take density 1.2256, V star is nothing but already you are a specifying your aircraft should fly at a minimum at least 30 meter per second.

And see if you are taking off you will deflect flaps to generally C L max will be 1.1 to 1.5. But you without flap deflection, if you deflect the flap your C L max will increase. So, in the present case 2.3 value I am taking just see the book aircraft performance and design by J. D. Anderson you will get this value. Remember that flap is the device which is used to increase the C L maximum, it is always deflect in the downward direction.

And usually we will disturb the flap in a takeoff or landing motion, we do not generally disturb the flap in a cruise condition. Generally if we want to made more lift like in during the takeoff if you want to cover the shorter distance if you are taxing in the runway, if you deflect the flap you will get more C L, so at a minimum speed you can takeoff, ok. So, if you put this value what you will get your wing loading will be 129.306 kg per meter square.

That means 129 kg is capable 1 meter square is capable for lifting the 129.30 kg weight, this is a beauty of wing loading. But see you are taking only one phase, you are calculating the wing loading based on the stall approach that is not enough. Our aircraft flying as a stall condition as well as design cruise speed, in takeoff also, in cruise also. So, we have to take that case also, we should not limit our calculation to this a stall conditional only. So, let us say we are cruising from 2 to 3 cruising and our design speed is 70 meter per second and our design C L is 0.4.

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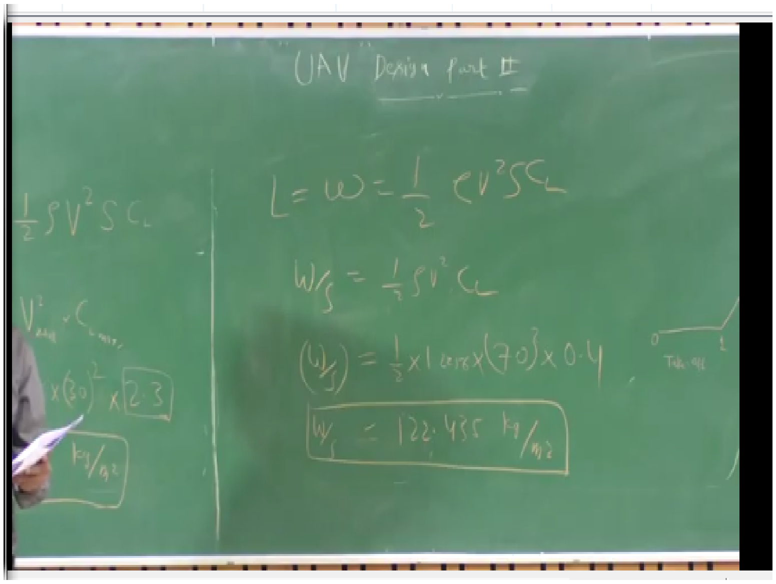

So, just rewrite the equation again the half rho V square S into C L W by S will become half rho V square not C L, it is C L, ok. Now W by S at your design speed you are flying at a sea level, your design speed is 70 at this design speed your C L 0.4, ok. So, you will get that of wing loading approximately first here if you calculate you will get Newton you just divided by 9.81 you will get 122.435 kg per meter cube.

This is your W by S at cruise speed because if you remember at the starting of the lecture the cruise speed is also given as a machine requirement, design speed. The design speed is 70 to 100 meter per second, remember. So, these two approaches I have calculated wing loading based on this cruise condition and based on the stall approach. You can say not cruise condition, one is stall approach, one is design speed, ok, stall speed, design speed, ok. In from these two approaches we have calculated and since we are deflecting the flips.

That means this is nothing but the takeoff phase and this is nothing but the cruise phase, ok. So, I want to give one exercise you just calculate the wing loading based on the landing like takeoff you have, cruise you have, you just do the calculation for landing. I have done I will attach this material like based on the landing I will attach in this week as a separate extra material. But before that I will request you to find out the wing loading based on the landing approach, the book names I have already given to you, ok.

So, now you have wing loading, right, and that means if you have weight you can find out the area. So, area wing area, see our primary purpose is to find the wing area, how much wing area is required in order to lift the weight which we have found out in the first step after so many calculation, right.

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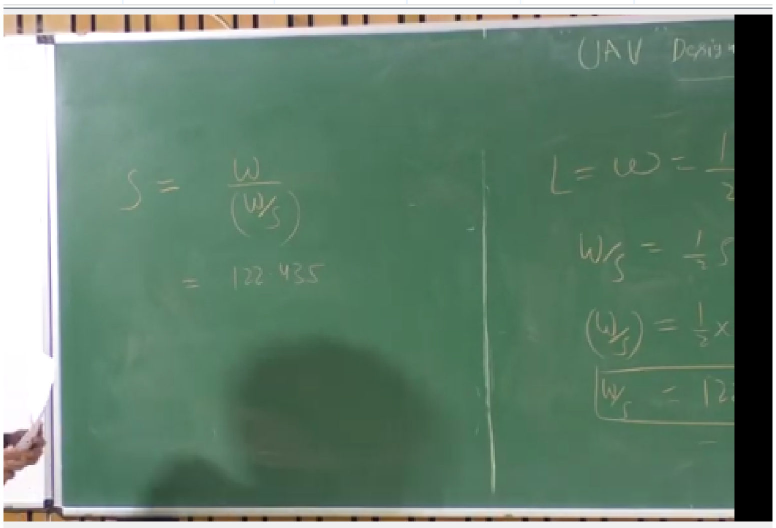

So, wing area you can write S is nothing but W divided by W by S, right, so see you have calculated 2 wing loading, right. One is from stall velocity approach and one is from cruise velocity approach which one you will select? You just think about this and please post in the forum like which see it is very close to each other but which one will you select? So, I am selecting as a cruise condition which is design speed.

You can also select from the stall but if you are selecting this wing loading instead of the wing loading which we have found out from the stall approach. There is a some difference when you fly from 0 kilometer to 5 kilometer like, when you are calculating from that takeoff approach means your W 0 is at the starting value, when you are cruising your fuel is getting consumed, so there will be some difference.

So, I want to know these difference, I am giving you as exercise k what is the difference between if you consider this wing loading and that wing loading which you have find in stall approach, ok, you just take W is how much?

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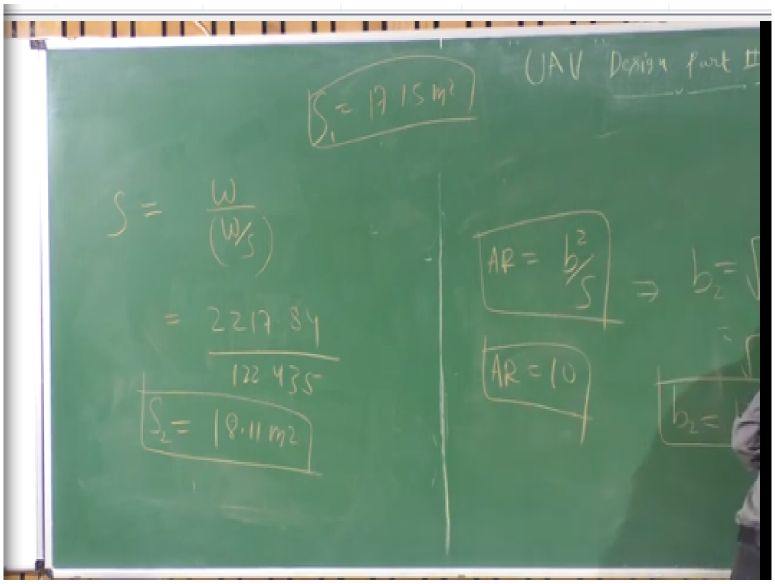

W is nothing but 2217.84 and W by S nothing but 122.435, this is nothing but 18.11 meter square, this is area, ok, 18.11 meter square area. This wing loading correspond to that design speed, if you take the stall wing loading, that means the wing loading which you calculated at the stall speed, you will get S is 17.15 meter square, ok. There is a one term in aircraft design which is aspect ratio. That tells the how wide your aircraft is compared to the span wise length like.

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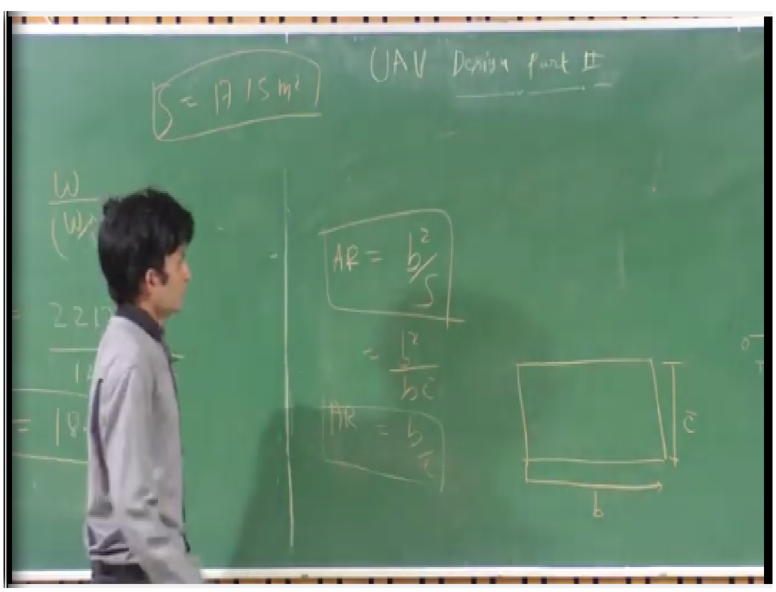

Aspect ratio is nothing but the b square by S and for rectangular wing, this is your span, this is your chord C bar or C, area you can write b into C bar b, b will get cancel, so b by C. like suppose that this is your wing, so this is nothing but the span, so this is consider as a length and this is as a width. So, how long compared to the width that basically as per ratio, this is for rectangular wing and this is for journal any case tapered swept by everywhere this formula is value.

So, this is also one the selection criteria for designing aircraft like you might have heard like glider aircraft, fighter aircraft, commercial aircraft, general aviation aircraft. These aircraft belongs to the particular class of aspect ratio like glider has a high aspect ratio you can see glider has a very large wing span, very large span b square as per ratio will be higher. Fighter aircraft very short wing, less as per ratio b will decrease as per ratio will decrease.

General aviation aircraft like as per ratio 10, 11, 12, 13, so basically what aircraft we are designing that belongs to the general aviation aircraft. Basically the trainer aircraft where that means 4 or 5 passenger will be there 1 pilot will be there, 1 co-pilot will be there max to max 6 persons 6, 7 like.

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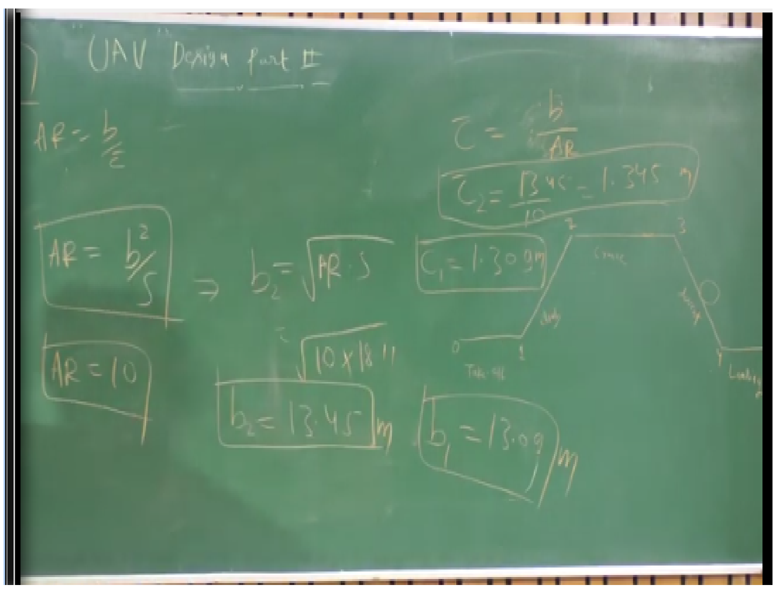

So, as per ratio you just assume 10, ok, so you know the area, you know the as per ratio, you have assumed, right. You can find out the how much is span of the wing, so this is nothing but 10 into 18.11 you will get 13.45, this is span. If you calculate from the another part if you put S = 17, you will get span you just second approach put 2, put to 1 here, ok, you just put 2 here, it is better and b 1 will be 13.09, little difference is coming, ok.

See generally when we are designing our aircraft we will do the optimization later, first we will do the primary design, after that we will do some optimization, right. So, let us say we do not have any tapered, sweepback, dihedral, that is things will come later. Simply we are taking rectangular wing in the present case for later we will do the optimization. So, C bar will be nothing but from this equation, ok, for rectangular wing aspect ratio already I told you b by C bar, right.

So, C bar will become aspect ratio by b, so aspect ratio is 10, ok, b by aspect ratio, right, b is you have find out, right, how much 13.45 just divided by 10, 1.345 meter. You have two b various specific in terms of unit which is meter everywhere, C bar. That means c 2, second approach, right. And from first approach C 1, that means you are calculating based on the stall approach 1.309 meter, little difference is there.

So, now your wing sizing is now completed, first is weight estimation for that particular weight you require the wing, you design your wing, area is this much, span is this much, your wing chord should be 1.309. So, this is nothing but the wing sizing but see you are taking off, climbing, cruise, descending, landing where you will get the power? See you these things lift, where you can get lift?

When you are aircraft flies like you need some velocity, where you can get that velocity? You are not falling any under gravity like so you are going climbing against the gravity from where the power will come? So, basically from the engine the power will come, so in the next class I will explain about the how to select the engine? Like to meet the specific requirement for taking off from 0 to 1, climbing from 1 to 2, cruising from 2 to 3, descending from 3 to 4 followed by landing from 4 to 5. So, how will you select the engine? That I will discuss in the next class, thank you so much.