Design of Fixed Wing Unmanned Aerial Vehicles
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Lecture - 16
Iterative Weight Estimation and Wing Sizing

Dear friends, welcome back. In our previous lecture, we discussed about weight estimation of electric powered propeller driven UAV.

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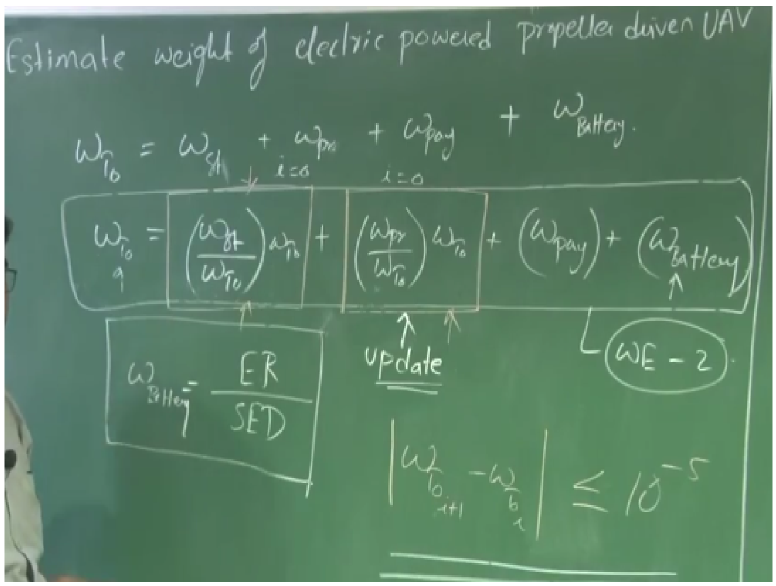

Where the total take of weight us a summation of structural weight, propulsion weight, weight of the propulsion system, weight of the structural system and of course there is a pay load, which is guided by the mission requirement and then what you have is fuel weight or battery weight. We can express this equation in terms of weight ratio and propulsion weight ratio times the total take-off weight and pay load is a given input and value battery need to be estimated as per the requirement, right.

Now in our previous lecture, we solved an example where we figured out what should be the weight of the battery depending upon the energy requirement of the system. Energy required/specific energy density is a total weight of the battery required with some efficiency factors. So by using this, we estimated the total weight of the battery. While doing that, we assume there is a known take of weight.

Take-off weight is known, but say if you are starting a new design of new UAV where you have only a set of mission requirement, but you do not know what is the overall take-off weight, how to start or how to solve that problem, so the approach that we are going to adapt here is an iterative approach.

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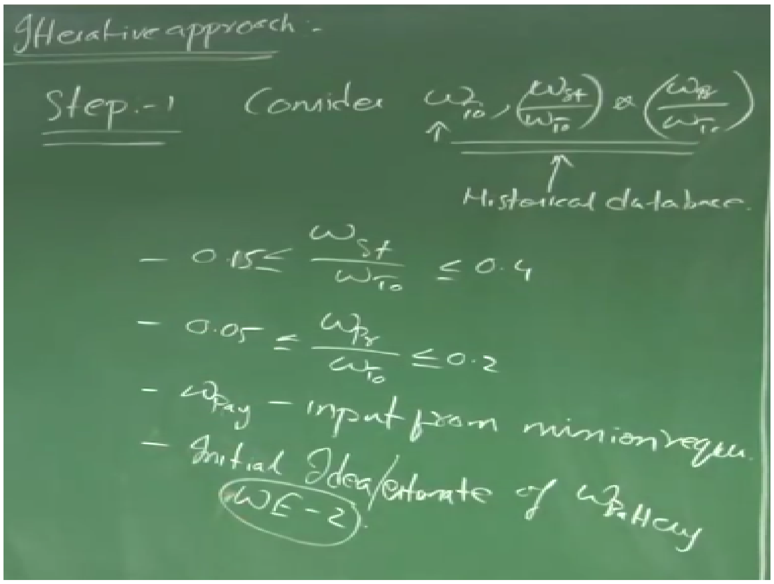

How we are doing this? Now based upon the pay load, weight of the pay load or the mission requirement, you can consider a nearby UAV, an UAV, which can perform the similar, may not be the same, but close to that. You can consider the data of those UAVs, right. From those UAVs, step 1 consider W take-off, to start with W structural/W take-off and W propulsion/W take-off, so consider these three parameters from the historical database.

So typical value for a fixed wing UAV, the ratio of structural weight to take-off weight ratio for a fixed wing UAV will range from </= 0.35, 0.15-0.4 and typical values of propulsion to take-off 0.2 is the maximum, where we are considering and will lay 0.05, 5% of the overall take-off weight. And now, you also consider the input of this overall take-off weight.

So by doing so, what we have this is, this equation that is presented here will talk about the UAV, which is closer to the current mission requirements. In fact, this represents exactly the same weight estimation of that previous UAV. Now what we have to do is, bring this equation to the current UAV, current mission. How we are doing this. So initially by estimating, you know the pay load and the mission requirement.

So that means, this is known. Let us say if this is known, then using these parameters, you get to know what is the battery weight, right. By doing so, you can estimate initial idea. We can get an initial idea of this batter weight, where W pay load is an input from initial requirements, right. So using this equation, we can name it as W weight estimation 2 or 3, what is the number. Say this is W2. So you will get the initial idea of weight of the battery using WE2.

But we are not going to use that. That parameter is not of use right now. So with this take-off weight, let us say and you are going to perform mission that is of current requirement, with new mission requirements. So that means, so this weight of the battery. You are estimating the weight of the battery from here, right, which is from the previous UAV data. Then, ultimately you will end up getting the weight of the battery for the previous UAV, right.

But now, we want to figure out what should be the weight of the battery for this particular mission requirement. So how to do that? The same procedure, like we need to know what is the energy required for this particular mission or the new mission and you should know what is the corresponding specific energy density of the battery. So how we proceed?

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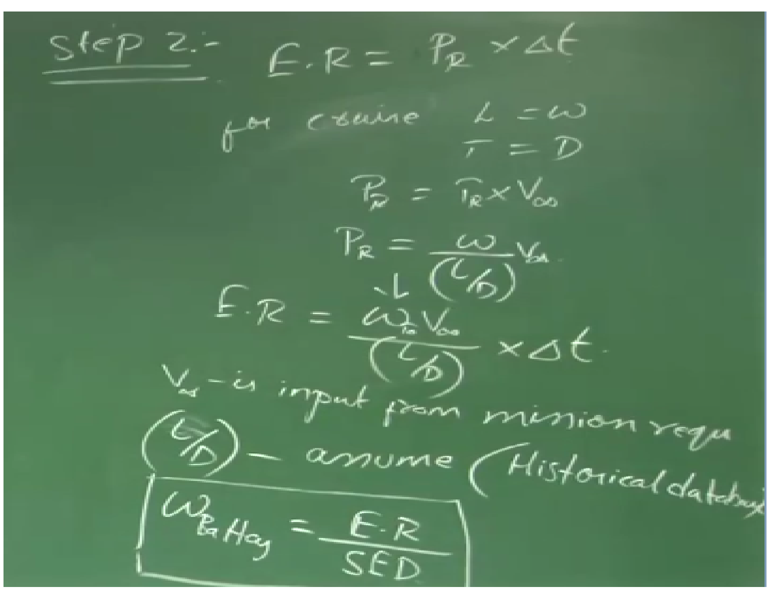

So the major consumption of this energy is during the cruise that we have witnessed. So let us start with the cruise. What is energy required? It is the power required into delta T, time of light during cruise, right. How do you get the power required? For cruise, you have L=W, T=D, so what is power required. This is trust required * velocity. What is thrust required? It is W/Lyd*velocity. So substitute this in the above equation, energy required equation.

So substitute this power required in the energy required equation to get weight of the system or the total take-off weight*V infinity*time of flight/L/D. So V infinity will be a part of the mission requirement. So how to get this? So V infinity is input from mission requirements. V infinity can be directly or indirectly can be derived from the mission requirement, the velocity of cruise flight.

So you have the previous UAV data, that is the take-off weight that you have considered the nearby UAV, which can perform similar mission. You WT not, so you have V infinity, but this delta T is different and you can assume a value of L/D. L/D is also known as aerodynamic efficiency. So assume, so typical values of L/D will be 8-12, 8-14 for a normal UAV, which is with an aspect ratio of 10 around.

For a glider kind of UAV, L/D ranges from 15-20, anything between that. So these values can be considered as an input from historical database. So the only assumption that you have to do here is what is the corresponding L/D. Once you know the L/D, you have WTo and V infinity and the time of flight, so you can figure out what is the corresponding energy required. Once you have this energy required, you can estimate the battery weight, which is equal to energy required by specific energy density.

You can do a market survey, where you will get to know what are the different types of batteries that are available and the corresponding specific energy density. So you can select one of those and use that number here to figure out the corresponding batter weight for this particular mission. So what are we doing. We have W take-off from the previous aircraft and whatever the battery that you have estimated, is for this particular mission.

Because this delta T, V infinity, L/D are this particular mission required. Now once you have this number, you go back to step 1 again. Where you can estimate this W battery using this equation. Now update this W battery value with the step 2, result from the step 2. Try to update this battery value, so once you have updated this, you keep these 2 parameters constant during this initial iterative process. For the time being, assume these 2 terms as constant.

During the first iteration, once you assume the value of ST/Wto and PR/Wto, multiply by initial weight of the UAV, which is again from the historical database. Now fix these 2 values, you do not iterate these 2 values. The only thing is we are trying to change the battery. While considering the M as a constant what we are assuming is, the structural weight and the propulsion weight are good enough to satisfy the UAV with the current requirement.

So that is the initial iteration to start with. So what we are trying to do, we are adapting this equation to the new UAV by updating the battery weight. Now you have updated the battery weight, the overall take-off weight again changes. Now for the new take-off weight, again the energy requirement changes, why because you have as energy requirement as a function of take-off weight. Now again estimate what is the battery weight here.

Now update this equation again with this battery weight. So you need to update this until this cost function becomes very less. You can define this error, right. So W take-off i+1-W take-off I should be less than or equal to some error. You can define this limit of this error, right. So if you keep iterating this, finally you will end up having the battery weight to satisfy this particular mission requirement. Once you arrive at this number, this cost function satisfies.

Now what you do is update the propulsion weight. How can we update? We already looked at how to figure out an engine based upon the power requirement of the system. We are actually calculating the power requirement here. Now you see what is the maximum power requirement based upon this mission requirement and try to select a particular engine, right. Now once you have the engine, you will have accurate weight here, almost accurate weight.

Now update this particular parameter and moreover we know that power plant can deliver a range of power. It is not that it is designed only for a particular power requirement. It can deliver a range of power, right, so that means a selected power plant can take care of the change in the battery weight again. Because now you have an updated weight here. What happens is again the overall take-off weight changes because of it.

Now you have to repeat this process again to update the corresponding battery weight. See we are slowly adapting the equation of the previous UAV to the current UAV to satisfy the mission requirements, right. Now the power plant is updated, which is selected by means of based upon the power requirement of the system as per the new mission requirements. Now you have updated this parameter, right, again do the iteration, fix this value.

And this is again considered as a constant or that new take-off weight after this iteration. You can consider that as an input here. You can update this assuming the same structural weight ratio and you have the new take-off weight, update this parameter and make it as a constant for the second round of iterations, right. So again you end up having a different battery weight, right.

The final battery weight due to the updated propulsion system weight as well as the updated structural weight, right, is arrived by means of minimizing this error, right. We will write the steps for this. So once you have that, then you can consider this equation for this weight estimation for this current UAV. Now once you have this battery weight as an output of the second round of iteration.

So this particular take-off weight whatever you are going to get is an estimate for the UAV that you are going to design for the new mission requirement, right. As we mentioned, it is an estimate, right. Some of those parameters are assumed, so it is an estimate which may like you can assume a 20% of error using this procedure. Whatever the weight that you are going to arrive at will be 20% off from the actual value, right.

You are having an accurate weight of this propulsion system, the only thing is once you have the structural weight ratio or once you design the structure you can update this parameter again and do the iteration, but to start with or the initial weight estimation, you can adapt this procedure and this is fitting with almost 50 UAVs, right, data of 50 UAVs that we have verified and this procedure you can adapt to figure out what is the overall take-off weight and the corresponding battery weight as well as what should be the propulsion system that you have to use.

And for a given pay load, right so the other way that I look at it is, so within this limit you have to design your structure. You have to optimize your structure within this particular limit. That is another approach, which can be adapted so that the weight from each and individual components will satisfy this particular equation. So what are we doing now. So step 1 is, I am repeating this again. It may be a bit confusing. So what we have done.

The total take-off weight is the summation of structural weight, propulsion weight, payload and battery, right. So this equation can be expressed in the form of weight fractions, right. So the take-off weight is have a component of or a function of structural weight ratio, propulsion weight ratio, right a later propel device. We are not considering battery-weight ratio here. So electric powered propeller driven aircraft, this equation will give an estimate of the overall take-off weight, right.

Now this parameter W structural weight fraction is taken as an input from the historical database as well as the propulsion weight fraction is taken as an input from the historical database. Now you have these 2 parameters and to start with, we are considering the overall take-off weight of UAV, which is close to this particular UAV that you are going to design as per the new mission requirement. So the 3 inputs that you consider is W take-off. This is at I=0, at 0th iteration.

To start with, so W take-off and structural weight fraction and propulsion weight fraction. Now once you have this, so with the same equation, what you can find out is the battery weight with a new payload that you are going to carry. This is an input here, payload is an input here, right. At I=0 you have what is the corresponding battery weight. What should be the corresponding battery weight for this new payload to carry.

But the propulsion weight as well as the structural weight ratio and the overall take-off weight are considered from the historical database. Say with this overall take-off weight, with the new mission requirements, now find out what is the corresponding battery weight, how to do that. Now the power required here is W/L/D*V infinity. Here W take-off is from previous UAV or the historical database and V infinity is as per your new mission requirements.

Delta T is as per your new mission requirement, the time of flight and L/D is an assumption that you are considering, right. So with the same L/D finally when you design the UAV, like when I say the design, when you select the wing area, you can achieve the same L/D, right, you can try to achieve the same L/D with that particular wing or a wing and tail combination. So this L/D is an assumption, which you can use at a later stage as well while designing.

So selecting this L/D is a crucial part, higher the value, lesser is your energy required or greater is your time of flight. So that we already witnessed, right, during what is the maximum endurance or maximum range, during that conditions, we also witnessed it higher L/D or CL power 1/2 or CD max or CL power 3/2/CD max, so there are various conditions under which you can achieve maximum range, maximum endurance, right.

So you have to select from one of those as per your mission requirements, you can select a nearby value, may not be the exact, it is an estimate again, ultimately. So once you have this energy requirement with those inputs, you can find out what is the corresponding battery based upon your available specific energy density of the batteries. Ultimately whatever your designing, you should be able to realize it, right, you need to make it.

That means you cannot have an estimate of, you need to consider a realistic value, say CD of 0.1 is realistic, 0.2 is also realistic, but considering 0.5, when I say 0.5, the units are in kilowatt hour/Kg, 0.5 is a futuristic thing, which is not readily available. So you need to find out the access that you have for various energy density batteries, right. Right now, we are having an access up to 0.25 kilowatt hour/Kg, right, if somebody finds a higher CD battery, please let me know.

From here, you can figure out what is the weight of the battery. Now go back to this equation. So for the same UAV, let us say if this battery turns out to be the same battery weight, so at I=1, you will be able to converge, because nothing is going to change here. The same UAV, which is available can do the new mission requirement, whatever you have considered, but the mission requirements are different, maybe the velocity may be different or the time of flight may be different.

So generally, you do not end up having the same battery weight. That means, you are updating the overall take-off weight. This is the first step where you are bringing the weight estimation of previous UAV to your current UAV. That means, you are updating this Wto by updating this W battery and while doing this, we considered these 2 parameters are constant, which are the values at I=0. You use I=0. Do not update the Wto of this particular fraction.

And do not update the Wto here as well. You consider whatever the value that you have at I=0, consider it as an input for the entire iteration or initial iteration, entire initial round of iteration, right. So repeat the step, now since the Wto is changed, again the overall take-off weight is changed, then the energy requirement to perform this particular mission will change. So once you change this, what you have is, you knew battery weight.

Assuming the same L/D and the mission requirement still remains same, since the Wto is changed, slowly you are trying to bring it to your current UAV, so your energy requirement also changes. So this change in the energy requirement will reflect in the total battery weight that you have to carry. Now again update this battery weight, you will have new take-off weight. Again repeat this process.

So you have to repeat until you arrive at this cost function or this cost function is satisfied, right. Now once you have that, what you have to do is, see this particular term you have updated as per your new UAV, right and this payload of course, from the starting it is as per the mission requirements, that means it satisfies the requirements of the new mission. From this equation after this initial round of iteration, you have updated the overall take-off battery weight as per the new mission requirement and the payload is, of course an input from the mission requirements.

Now it is time to update propulsion weight. Weight of the propulsion system. How to do that? We already figured out how to select a power plant based upon the maximum requirement, right either rate of climb or the cruise. So from here, this is just for cruise, you can also add for rate of climb. What is the energy requirement during rate of climb? That adds up the total energy requirement, right.

Now again, you know what is the power requirement during various phases, what is the maximum power requirement. Now based upon that maximum power requirement, try to select a power plant. So while selecting this power plant, the only care that you need to take is, whatever the maximum power required, it should be delivered by the power plant at its 50-60% of its operating power, right, that will help you even if the battery weight again changes.

Because once you select the power plant, this particular term is updated. The overall take-off weight is again getting update, right. That means you have to know what should be the corresponding battery weight or the fuel. In general, it is a fuel, but in case of electric powered propeller driven, it is the battery weight, right. So now since this parameter is updated, you have to update the corresponding battery weight.

Now consider this or update this value, at the same time after this convergence here, which is arrived after the first round of iteration, you update this structural weight as per the take-off that is obtained after this convergence. So that is again updated. So what are we doing. We have an updated battery weight, we have a payload as per the new mission requirement and your propulsion weight is also updated as per your new mission requirement.

And now you are actually updating the structural weight, but in this case you are still considering the structural weight ratio, right. You still have this ratio as an input from the historical database. Since the weights are updated here again the total overall take-off weight changes, that means the battery weight need to be again estimated. Now do the second round of iteration, right.

Second round of iteration again estimate with the increased take-off weight estimate the corresponding energy requirement and the weight of the battery and update the take-off weight and iterate this process until this cost function is satisfied. So this is the second round of iterative process. But, the advantage, again you can ask like see the power requirement again changes since the take-off weight changes here, even after the second iteration.

But we are considering the power plant whatever we are selecting here by doing with this algorithm, we are selecting a power plant that can operate at a 50% of the maximum requirement, right. So this will take care of say 20-30% of increasing the power requirement. Similarly, the structure whatever you are going to design, it will have a factor of safety and so the aircraft or the UAV that is designed to carry 3 kgs, will not change for 2.5 kgs.

The structure may not change significantly for 2.5 kgs. So that factor of safety, you need to consider a higher factor of safety, so that this iterative process can be minimized or the rounds of iteration can be minimized. So maybe in the first round, it may take 10 iterations, in the second round it may take another 10-15 iterations to converge. So after 2 iterations, it is like more or less a good estimate of initial take-off weight for your particular UAV, right.

This is the whole iterative process; you can numerically solve this by using MATLAB or any of the programming language. So I have something for you right now.

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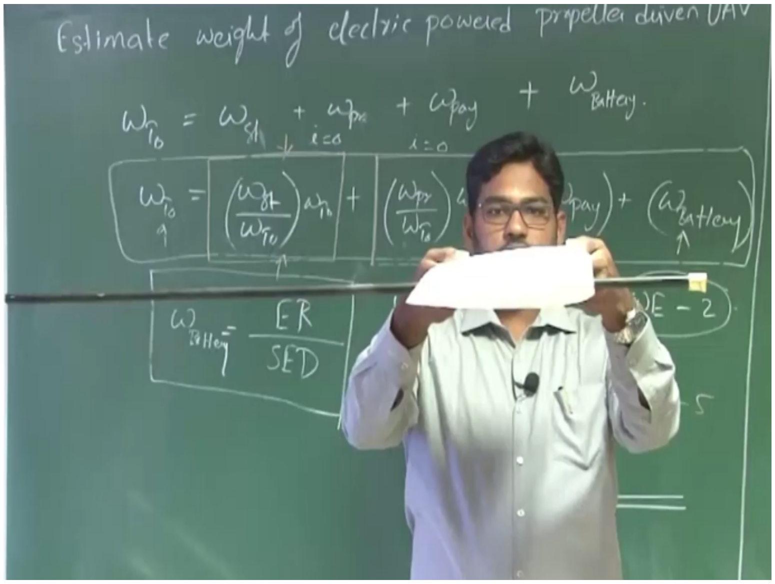

It is a symmetric wing. I can see a bit of what you call asymmetry, but that is fine. It has symmetric wing made out of symmetric aerofoil, right. It is of 1-meter span. There is a boom that is helping me to hold this, particular wing, right. So this book is passed through this to balsa wood blocks attached to this wing. Let us see what is the weight of this system. How can I do? Put it on a weighing scale. So is it 0 initially, yes and it is approximately 148 gms, right.

That is good. How much weight this wing can carry or with this wing what can be the weight, what is the maximum limit of the weight with which I can still fly, right. We will address that by wing sizing. Now let us write down the final steps how to find out the weight of the UAV or weight of the battery or the initial weight estimate of a UAV as per the mission requirement. Now what you have done?

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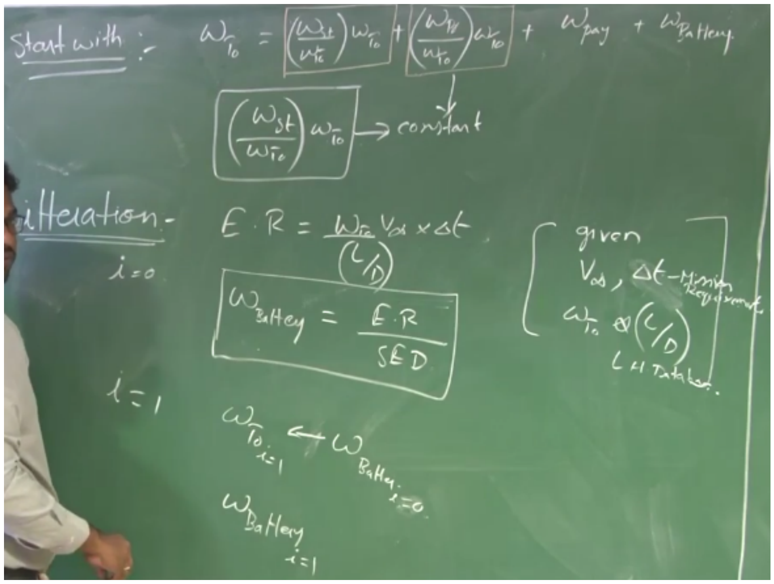

We have step 1 and step 2, right. Step 2 helps you to figure out what is the energy required, which is W/W take-off*V infinity*delta T/L/D, right and corresponding battery weight can be figured out by energy required/specific energy, density of the battery. So start, in this algorithm, what you have is to start with W take-off is Wst/W take-off * W take-off + W propulsion/W take-off right. You start with this equation and consider this as constant.

Which is a constant and this one also constant, right. So yeah, from the historical data, these 2 are constant, so you have W take-off weight now to start the iteration at I=0, you estimate what is the corresponding battery weight with this take-off weight, right with given V infinity, delta T, right and Wto and L/D from historical database. These are from mission requirements. These are from historical database, so SED from the market availability.

Do a market survey and get to know which kind of specific energy density batteries that you can get? You will get to know what is the other battery weight here. Now once you have the battery weight, you update the take-off weight, right. So with the new take-off weight, that I=1 you have updated take-off weight at I=1 with the corresponding battery weight at I=1. So this updated take-off weight, you obtain from the initial battery weight that you have estimated at I=0.

Now with this take-off weight, again find out what is the battery weight I. So this is obtained with I=0, the one that you calculated here. Now update this equation with this battery weight to get take-off weight at I=1 that is the first iteration step. You said 0, right it is an initial value and now the actual iteration starts here. So with this take-off weight, which is updated as per the new mission requirement with corresponding battery weight.

Now try to find out the new battery weight at I=1, right. Now after this first iteration, you have battery weight at the end of first iteration, right. Now find out the overall take-off weight at iteration 2, say I=2 right now.

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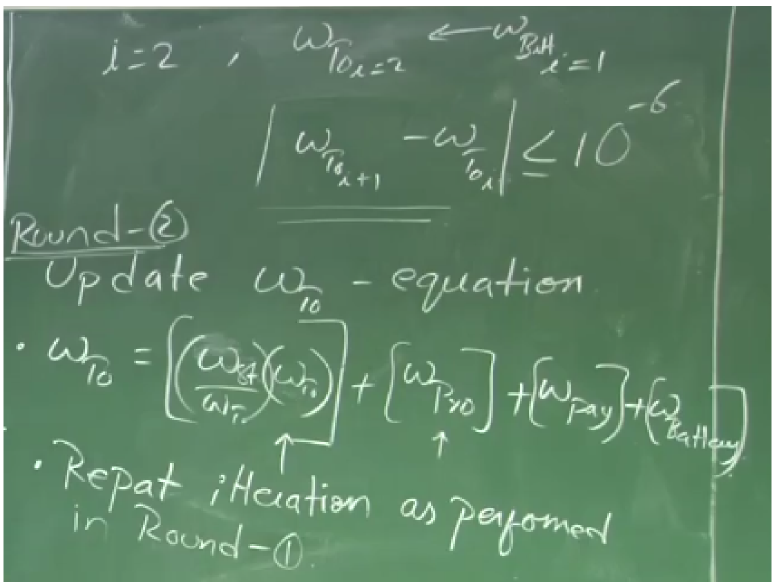

Now you are entering second iteration. Find out what is the take-off weight at I=2. This is the starting of I=2, which is obtained from battery weight, at the end of first iteration. So this is updated with the battery weight that is obtained. So before proceeding further you need to see whether take-off weight at I=1 or I=2-I=1, I is less than, ideally it should be, if it is equals to 0, the difference between them is equals to 0, then it is good.

Otherwise give certain limit 10 power -6, which is 0.000, right. If that is the case, then you can have, I mean you can consider that the new take-off weight as a updated weight and the corresponding battery weight for the new UAV, right. This is round 1, round 1, you do these iterations. After round 1, once you achieve this, what you do is update W take-off equation. That means what are we updating here.

Already we are updating the battery in each and every iteration. What are we updating here, the propulsion weight ratio? The total weight of the propulsion system. This you can figure it out by calculating the power requirement during various phases or the maximum power requirement and select a power plant that delivers this required maximum power requirement at 50% of its operating power, after all efficiencies, after considering all efficiencies.

So this should deliver the required maximum power at around 40-60% of its operating power or the maximum operating power, right. Now you have Wto, updated Wto, right. Why because Wto=say W structure, which is again a ratio. This is updated from here. At the end of this first round of iteration process, like the iteration, there can be n number of iterations in this first round. By the end of this first round, you will get a particular take-off weight.

Update that particular take-off weight here, with the same structural ratio, that means this particular structural weight is also updated as per your new mission requirement and you have the propulsion weight here. So propulsion weight can be readily considered as an input. Why because you are actually selecting a power plant and the details of the weight of that power plant are available from the manufacturer, right.

So this is again, it is not an estimate anymore here, right. It is an accurate value. Payload is an accurate value that you will consider + battery. But this battery is what the weight of the battery that you obtain by the end of first round of iterations, but since you have updated the propulsion weight as well as structural weight, these 2 parameters, this has to change again, because the overall take-off weight is changing. Now repeat iterations as performed.

This is round 2 of weight estimate, as per found in round 1 of weight estimation, right. So again you need to update until you get this cost function satisfied. So you will get the final take-off weight, the propulsion weight, payload as well as the battery weight by the end of this iteration process. Now once you have this weight, right and you know what is the velocity of light, as per the mission requirements, you know what is the altitude of your cruise, right.

You need to figure out what should be the area of the wing of the reference area, which I need to consider. So that is wing sizing.

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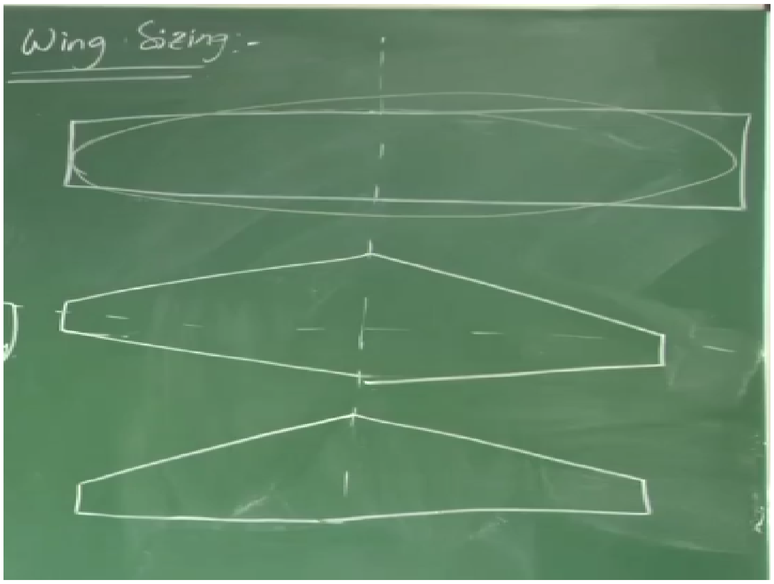

So how you are doing this, wing sizing. So what are the wing parameters in the first place. We discussed about some of the planform parameters, right. You can have a rectangular wing, you can have a tapered wing, tapered about midpoints of the chord, right. Tapered about trailing edge, right or an elliptic wing. So there can be many planforms, right. So what are the major parameters that we need to consider here while sizing the wing.

Why we need to do that and they are going to help us. These are the questions that need to be addressed, right.

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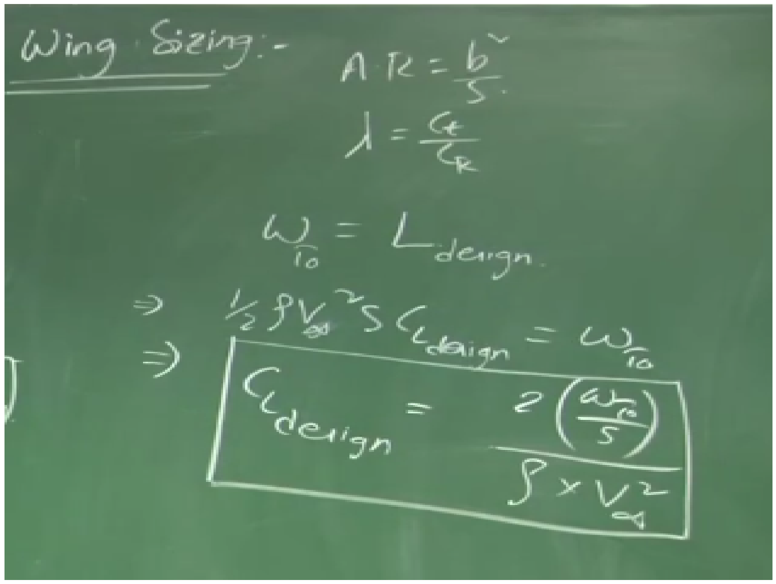

So aspect ratio, which is b square/s. We already discussed about it, various aspect ratio wings and the taper ratio CT/CR. So CT/CR also help you for the structural design, right. Why because as the taper changes, the lift distribution changes. The whole idea of the taper is to make it elliptic as far as possible, the lift distribution to be elliptic as far as possible, right and also as the taper changes, the amount of lift generated by each aerofoil changes there.

That means near the chord, near the root you will have a bigger root chord and as you progress towards the tip, you have a lesser chord, right. That means the lift generated near the root is higher compared to that of the lift generated at the tip, which means the bending movement about the root or (()) (43:01) reference line is more or less, let us say if you use a rectangular wing, the bending movement that is produced because of the lift at the tip is more compared to when you use a tapered wing.

That optimization can also be carried out by varying this lambda. So by varying the taper, you will also modify the lift distribution along the span. At the same time, it also helps you for the structural design, right and twist. If the root chord and the tip chord are of same aerofoil and say if the root chord is not aligned with the tip chord, then you will have a twist, geometric twist and you can also have an aerodynamic twist.

Where the chords of the tip and the root are in the same line or in the same plane, or say parallel plane to the ground, but the aerofoils are different. That means the lifting characteristics are different. By doing that, you can still very the bending movement, as well as the lift distribution. So there are 2 types, both of them have advantages as well as disadvantages, right. Geometric twist is really difficult to manufacture from a manufacturing point of view.

Aerodynamic twist, again in both the twist the issue is either geometric or aerodynamic, the issue is you will start losing the lift, right. When you change the angle of attack of the root and the tip, that means, as you progress along the span, you are trying to vary the angle of attack. The twist varies the angle of attack, which have affectively varies the lift, CL or the lift coefficient at that particular or the overall lift coefficient will be reduced compared to that of a untwisted wing.

But the advantage is, we want the root to stall first not the tip, that means you give a negative twist. You will reduce the angle of attack as you progress along the span or as you progress towards the tip, right. Why because we will have control surfaces ailerons, which is responsible for the roll control at the tips. So we will excite the ailerons to recover from the stall, so we do not want the tips to stall. That is the another reason why you need to have twist along the wing.

Now during this initial wing sizing, what we do is, we assume aspect ratio and lambda as inputs from the historical database, right. Now what this wing has to do in the first place? It has to generate lift to overcome the weight and make the flight possible, so the whole idea is W=L or the overall take off is the designed lift. So you have to design your wing to generate this lift, right. This is half rho, V infinity square*CL design=W take off, right.

So CL design=twice the wing loading/density at that particular altitude*velocity of flight. Remember this equation, right, we will discuss about how to arrive at this particular area for a given weight of the UAV and the altitude of flight as well as the velocity of flight, right. We will figure out what should be the corresponding CL design and the corresponding wing area, right. We will discuss this in the next lecture.