Introduction to Aircraft Design

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Lecture - 49
Tutorials on Initial Sizing of Military Aircraft

Hello, let us have a look at how we can do the initial sizing of a military aircraft.

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As an example, we have taken an aircraft called as Our F 16, which is a theoretical aircraft do not think it is connected to F 16 in any direct way. It is just an aircraft that has been theoretically derived from F 16 aircraft. So, it is a jet fighter aircraft single seater.

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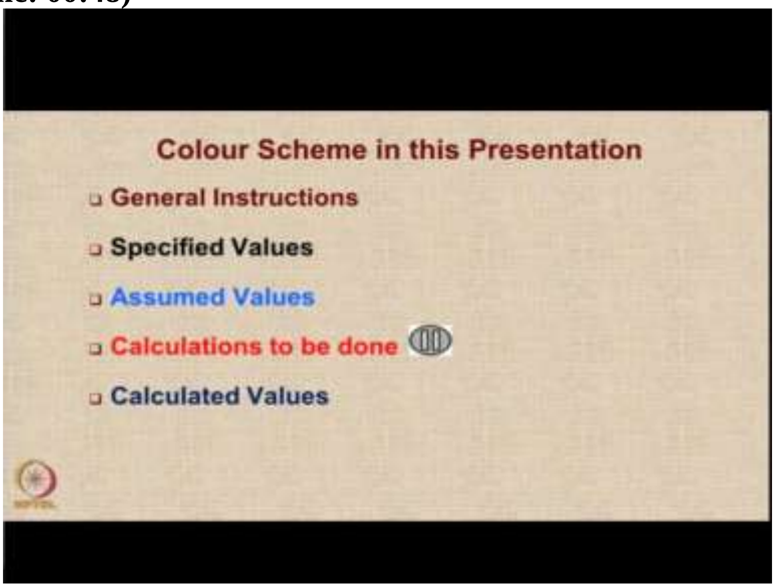

Before I start, let me discuss the color scheme in this presentation. So, the general instructions would be given in brown color, the specified values from the mission or from any other source would come or from data textbooks will come in black color, the assumed values would come in blue color, the locations where you need to do some calculations will be shown in red color. And there will be a pause button as shown here.

I would request you to pause the video at that stage do the calculations and then proceed further. The calculated values will be shown in the dark blue color. Now since this is a theoretical aircraft, we do not have any data to compare with.

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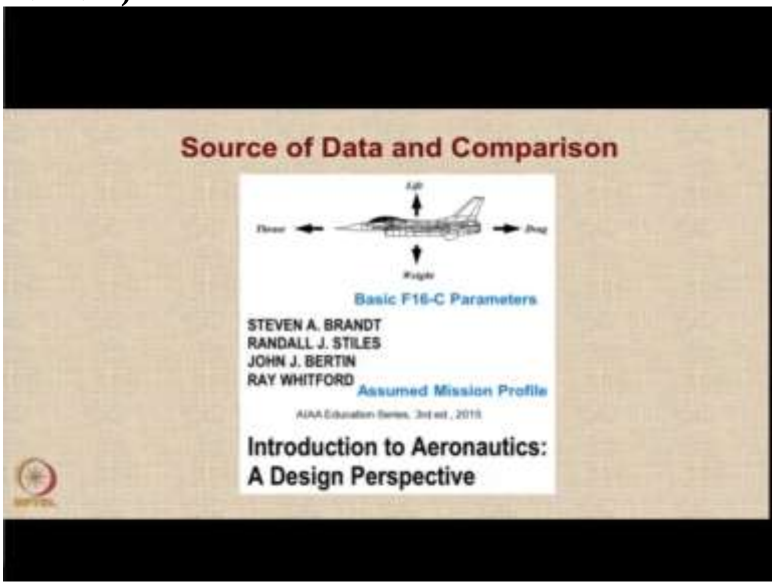

Now, the source of data in comparison for this particular presentation comes from the basic F 16 C parameters which have been listed in this textbook by Brandt, Stiles, Bertin and Whitford. And what we have done is we have used an assumed mission profile. So therefore, it has got nothing to do with what F 16 does.

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So, we will assume some data for Our F 16 C aircraft. The maximum payload weight is assumed to be 7575 kgs. This is similar to the maximum payload of F 16. The mass of the pilot along with the g suit is assumed to be 100 kgs, 75 kgs for the pilot 100 kgs total with all the paraphernalia, with the helmet et cetera et cetera. The SFC of the aircraft, the single engine aircraft in cruise is 0.8 per hour and the loiter specific SFC would be slightly more 0.81per hour.

But, when we go for a dash segment or a high speed flight at a very high mach number, supersonic Mach number, then the afterburner has to be used and therefore, the fuel consumption becomes at least 3 times more, so it becomes very high. The wing aspect ratio is 3.0. This also is closely matching with that of the actual F 16 aircraft.

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As I mentioned, we have assumed a mission profile for F 16 C that is why we call it as Our F 16 C.

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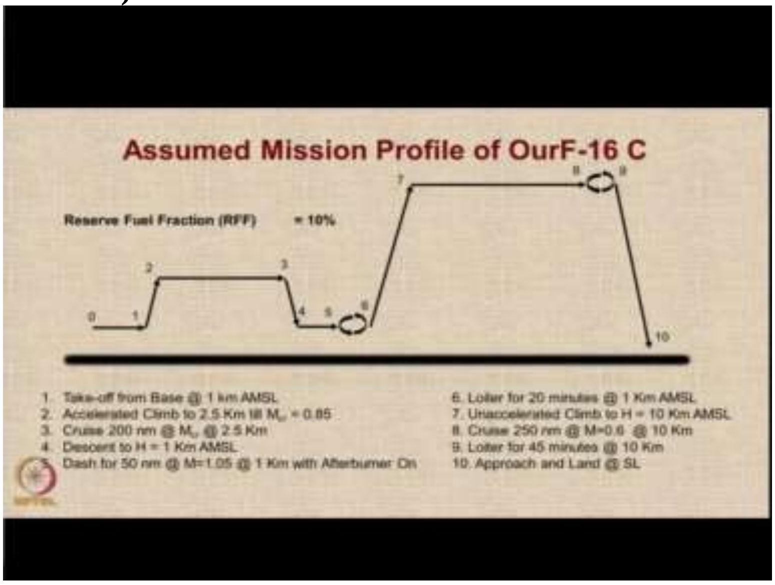

Our mission is the Low-High mission. So, you can see this is the mission profile. We start off by takeoff from a base which is at 1 kilometer above mean sea level the aircraft then climbs to a height of 2.5 kilometers in an accelerated fashion and reaches a mach number of 0.85 at the end of climb. We then cruise to the action of the location of action which is assumed to be 200 nautical miles away.

So we fly at the cruise mach number of 0.85 a distance of around 2.5 kilometers which means this aircraft is expected to be operating from close to the border. And therefore it just has to rush at a 2 and a half kilometer and then it climbs down to almost 1 kilometer above mean sea level and then there is a high speed dash at mach 1.05. So there is a supersonic flight at one kilometer with afterburner on.

During this phase a large amount of fuel is consumed because the SFC is very high. It is a short dash if just 2 nautical miles and then there is a 20 minute loiter where you engage with the enemy and undergo combat. This happens at 1 kilometer above mean sea level we assume the time is 20 minutes so during that time the aircraft is under loiter. Once the job is over, the aircraft is quickly made to climb to a height of 10 kilometer but this climb is unaccelerated climb.

So and then it actually cruises back to the base, it went 250 nautical miles away, 200 + 50. So now it actually heads back to 250 nautical miles. But this time it is coming back at a very comfortable mach number of 0.6 and at an altitude of 10 kilometers, and then we give another 45 minutes of fuel for it to loiter at that altitude. Because we do not know if there is any other requirements. So now you are at a friendly area and you are just loitering, you are ready for any further combat that might be needed.

Or you are in a protective mode in your own territory. After 45 minutes of loiter at 10 kilometers you then come back, approach and land at sea level. The reserve fuel fraction is assumed to be 10%. Notice that for transport aircraft, we assume it to be much larger but for military missions were assuming it to be just 10%.

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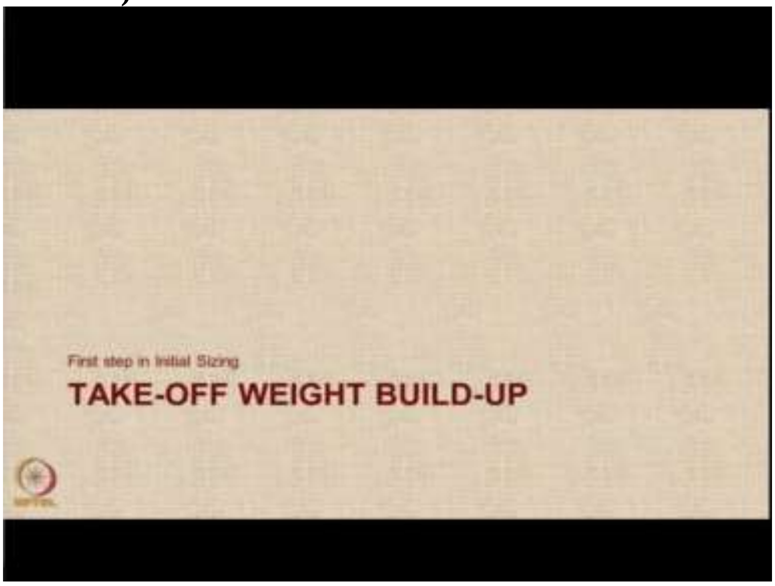

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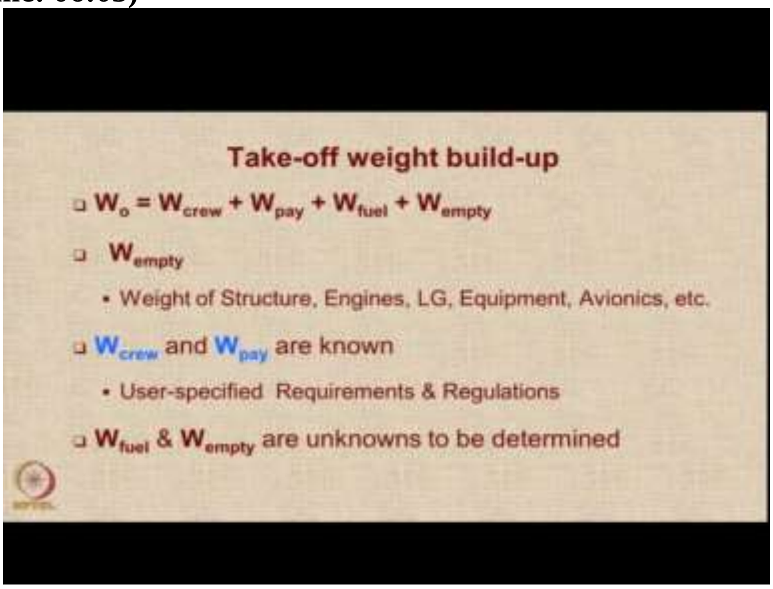

So let us look at the first step in initial sizing. Which is the takeoff weight built up. Essentially, we know that the gross weight W_0 can be considered to be a summation of 4 basic weights the crew, the payload, the fuel and the empty weight. Of these, the empty weight is basically the weight of the structure, the engines, the landing gear, equipment, avionics et cetera. Now, W_{crew} and W_{pay} are known from the requirements or from the specifications. So therefore, we know now, we have to look at the W_{fuel} and W_{empty}. Now W_{fuel} and W_{empty} essentially are the 2 unknowns which are remaining to be determined.

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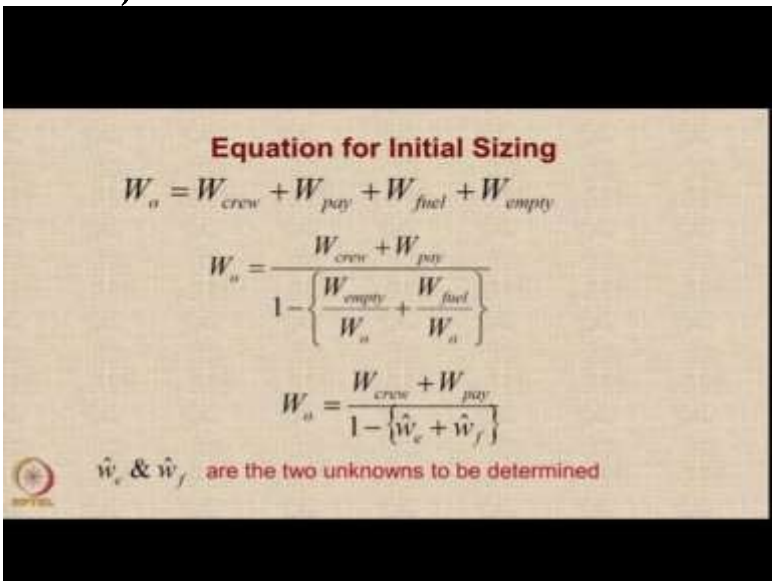

So what we do is we look at this master equation of force and then the known values are kept in the numerator W_{crew} and $W_{payload}$. And the 2 unknown values are taken in the denominator through a ratio $\frac{W_{empty}}{W_0}$, which is also called empty weight fraction or $\overline{w}_e$ and $\frac{W_{fuel}}{W_0}$ which is also called fuel weight fraction $\overline{w}_f$. So the 2 unknowns now are $\overline{w}_e\ and\ \overline{w}_f$. That is the only 2 unknowns to be determined. So these are the ones which have to be calculated.

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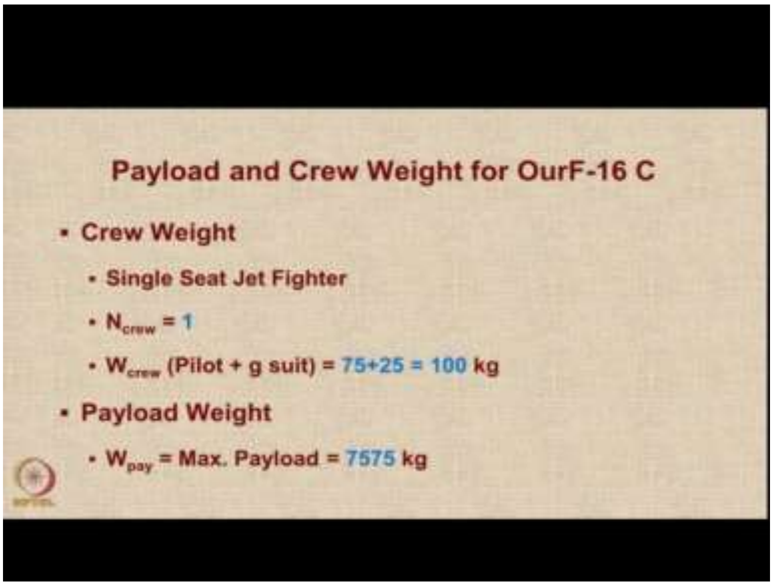

Let us look at the payload and crew weight for our F 16 aircraft that is the basic specification. As far as crew is concerned we have a single seat jet fighter aircraft. Hence we have just one crew member the pilot. And as I mentioned, the pilot is expected to, the pilot and the g suit et cetera is going to be assumed to be 100 kilograms. The payload weight is also specified here as 7575 kgs which closely matches with the maximum payload capacity of F 16 C fighting falcon aircraft.

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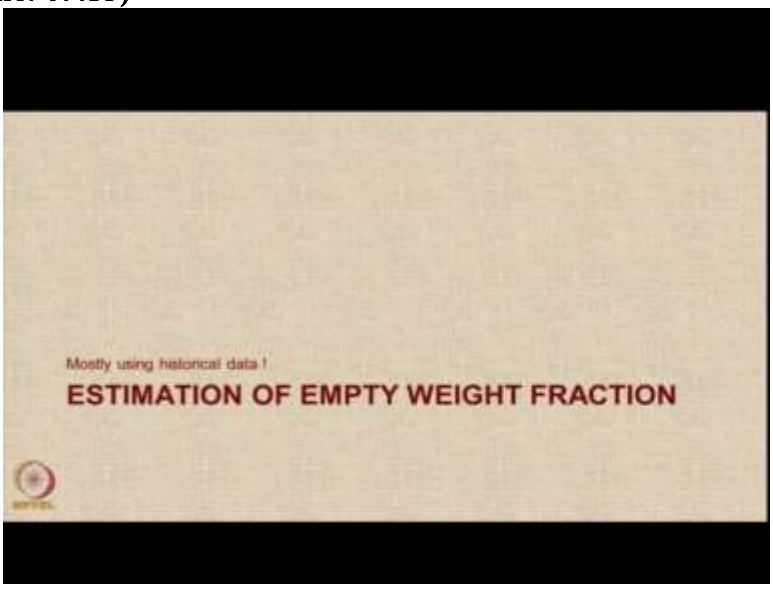

So let us start with the empty weight fraction and mostly we do it using historical data.

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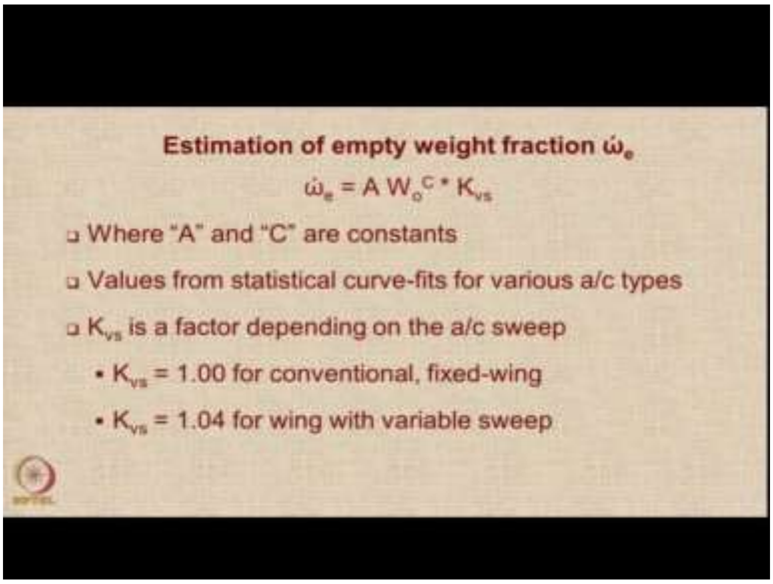

So, $\overline{w}_e$ is assumed to be equal to $AW_0^C K_{VS}$, where A and C are constants. These constants depend on the specific aircraft type. So we obtained the values for these constants A and C from statistical curves fits for various aircraft types. And K_{VS} is a factor that determines whether the aircraft has a variable sweep wing or a conventional sweep wing. In our case, we are assuming the wing to be conventional fixed wing, and therefore we will assume K_{VS} to be equal to 1.

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So let us look at the empty weight fraction trends. Data taken from a table given in Raymers textbook. Since we are going to work in metric units, we will look at A only in metric and C as you can see, there are different values for various types of aircraft. And these are the values of interest to us for a single seat jet fighter 2.11 for A and -0.13 for C.

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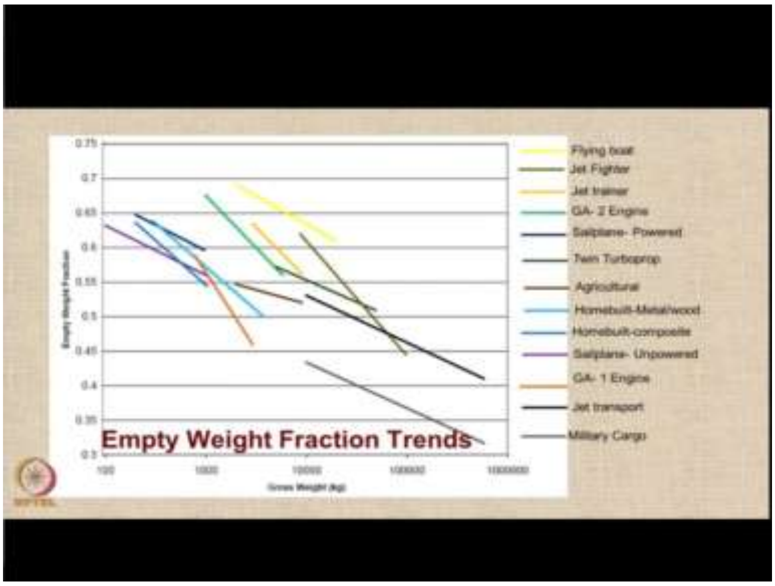

Let us plot these trends on a graph to see where all the lines lie. This is just for your information. So the flying boat normally has the highest values. And then we have jet fighters which is our category and after that we have several other types like jet trainer, general aviation twin engine, unpowered sailplane, twin turbo props, agricultural aircraft, homebuilt metal wood aircraft, homebuilt composite a bit lighter you can see the line is almost parallel to the metal wood line.

Then we have sailplane unpowered which are which is a parallel line to the powered sailplane on the lower side. And then we have general aviation single engine which is again almost parallel to the line, green line which is twin engine aircraft and then we have jet transport aircraft, this already will be, this already we have seen in case of Boeing 787 dash 8. And then we have the lowest ones which are the military cargo aircraft.

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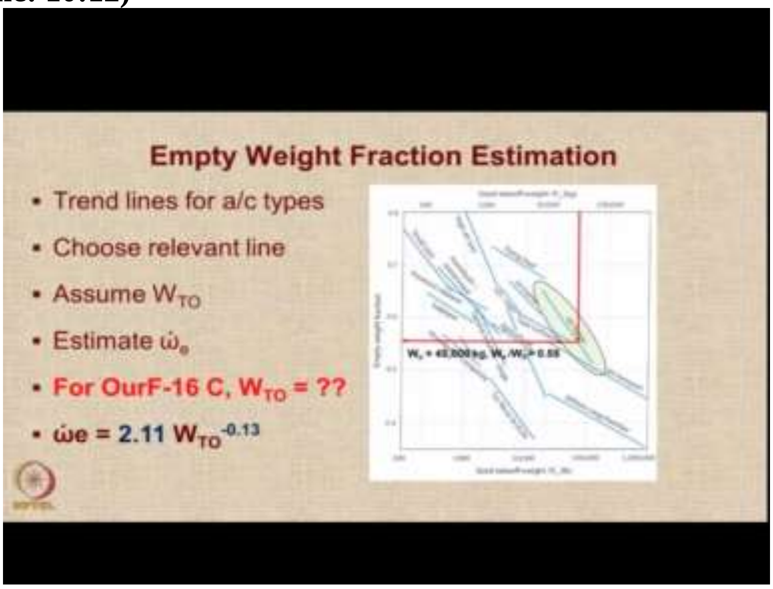

In our case, what we do is we look at these trend lines for various aircraft types. And we choose the relevant line for us it is jet fighter, and we assume some W_{TO}, and then come onto this line, and then we estimate the empty weight fraction by moving horizontally. So for example, if we assume the max takeoff weight to be, the size takeoff weight to be 45000 kilograms. For a jet fighter, it turns out to be approximately 0.55 as the empty weight fraction.

But what is the value for Our F 16. The problem is that for Our F 16, we do not know W_{TO}. W_{TO} is something that we want to estimate in initial sizing. So really, we cannot use this graph, what we have to do is we have to use the equation given by Raymer in which it is specified that the coefficients are 2.11 and the power is minus 0.13. So, we are going to use this expression in our calculations because we do not know the value of W_{TO} priory . So we cannot get empty weight fraction directly. We will get the empty weight fraction as a function of only takeoff weight.

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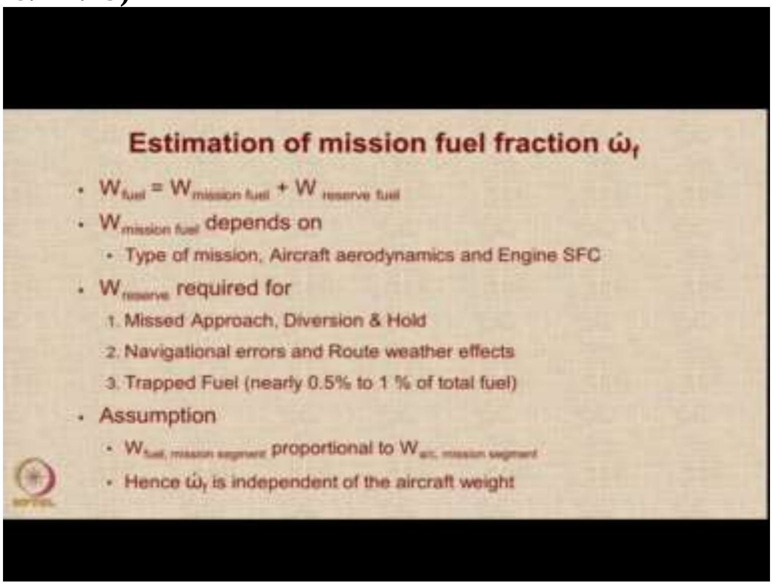

Let us look at how the mission fuel fraction is estimated. Just to recap that the fuel rate is equal to the mission fuel plus reserve fuel. The mission fuel depends upon the type of the mission or the aerodynamics of the aircraft and the engine SFC. Reserve fuel is reserved for all these situations which are beyond the normal planning. And then we have an assumption that we do not lose anything along the way in the mission except fuel. So therefore, the only way by which the aircraft loses weight is by consuming fuel. Hence, we can assume that the fuel consumption in any mission segment is proportional to the aircraft weight and only in that mission segment.

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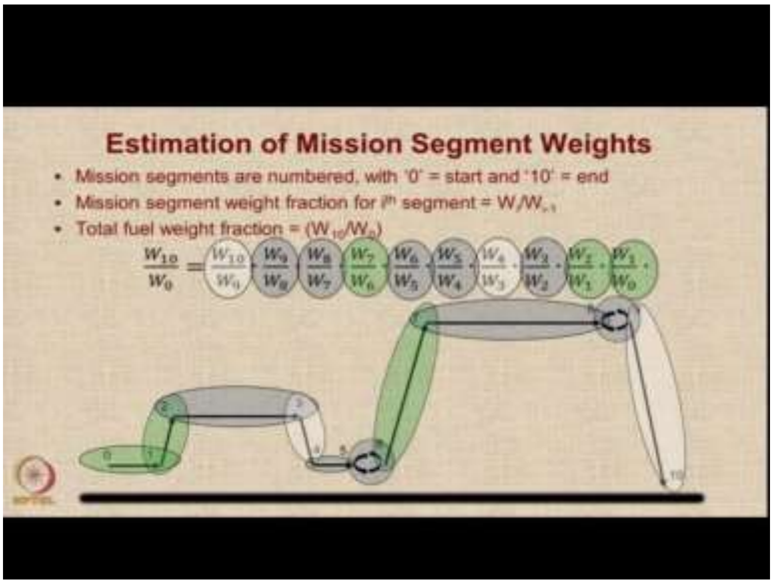

So, we can use the method. So, what we do is we number the mission segments from 0 to 10 in this case. And for any i^{th} segment, for any segment, so if there are 10 numbers there will be actually 9 segments. So, for any segment the fuel weight fraction would be $\frac{W_i}{W_{i-1}}$. The total fuel fraction would be $\frac{W_{10}}{W_0}$, which will be obtained as a simple multiplication of the fuel weight fraction in each of these segments.

Please remember that this is possible only if we assume that there is no other way by which the aircraft loses its weight except by consumption of fuel. Only under that condition this equation is valid. So, now let us look at how there are these terms to be calculated. We need these ratios. So let us see one by one. How for each of the mission legs, we can get the ratios. So for the first one $\frac{W_1}{W_0}$, we are going to use the prediction or the suggestion by Raymer to take the ratio as 0.97 which includes the fuel for warm up taxi out and take off.

Again for climb we will use historical data because this climb is actually a very climb to a reasonably low altitude although it is accelerated but it is to a very low altitude. So one can assume here that it is a simple climb. For the cruise segment of course, we have to calculate the weight fraction in cruise. For descent segment we are going to ignore the consumption of fuel that is why I put it in white color.

Then the dash segment is like a cruise segment but at a very high mach number. So even though it is a very small distance of 50 nautical miles, you will notice that there will be a large consumption of fuel. And then if we look at the loiter segment, for 20 minutes, there will be consumption of fuel there. So that also has to be calculated. But then when we go into an un accelerated climb to 10 kilometers, we again use historical data, just like the one that we use for segment 1 to 2.

For the return cruise segment of 250 nautical miles, we have to use the data regarding data related to the aircraft, we have to use the data related to the aircraft to get the values. And also finally, when we go for the last loiter, we need to look at the aircraft data. When we come into land, once again, it is a descent and approach so we ignore the fuel in that particular segment.

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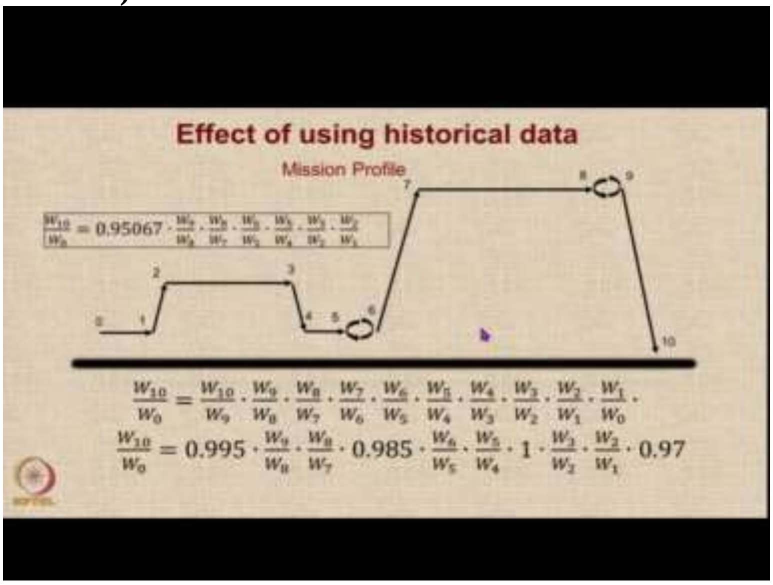

So as I mentioned, the warm up takeoff and landing weight fractions are estimated by historical trends and fuel consumed and the distance travelled during different segments is completely ignored. Effect of using historical data, this is our basic mission profile. And these are the 10 segments for which we had to estimate the mission segment weight fractions. But we can use historical data for this 0.97 corresponds to the warm up, taxi out and take off.

So, for that we use a constant fraction from Raymers textbook. This 1 represents the weight fraction in the descent segment which is 1 assumed to be 1. This 0.985 corresponds to the climb segment there is 0.995 corresponds to the landing segment and the remaining are the ones to be calculated. So therefore, what happens is that when you use these 4 numbers as constants, you ultimately end up with 6 numbers 1 2 3 4 5 6 ratios. For whom we have to do basic you have to do some calculations using the basic data of the aircraft.

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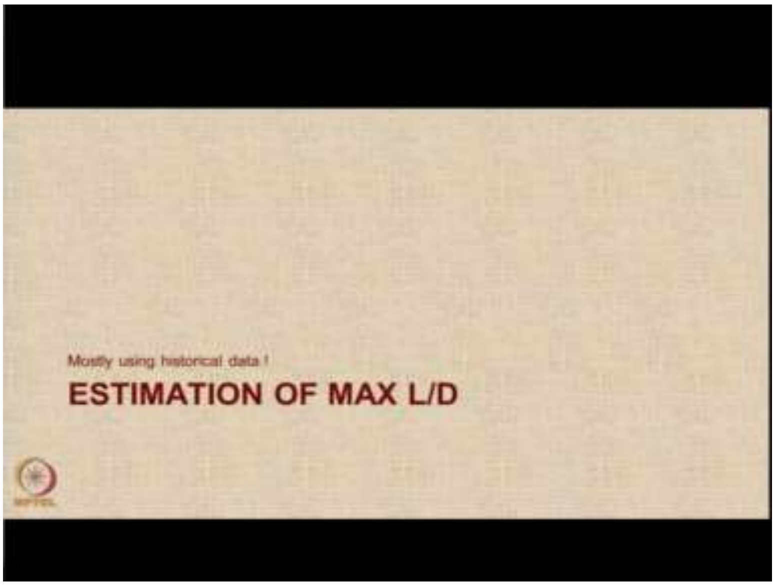

So, first start, let us first start with estimation of the maximum L/D which is done mostly using historical data.

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These are the approximate values of the cruise L/D max values for various aircraft types. And if we see military fighter aircraft, the L/D max ranges from 9.2 to 13.9 and the average value is 11.0. This is the one which goes for a subsonic cruise, our aircraft also goes for subsonic cruise, but the dash segment is of course, supersonic. So, L/D max average values is approximately 11 for such aircraft.

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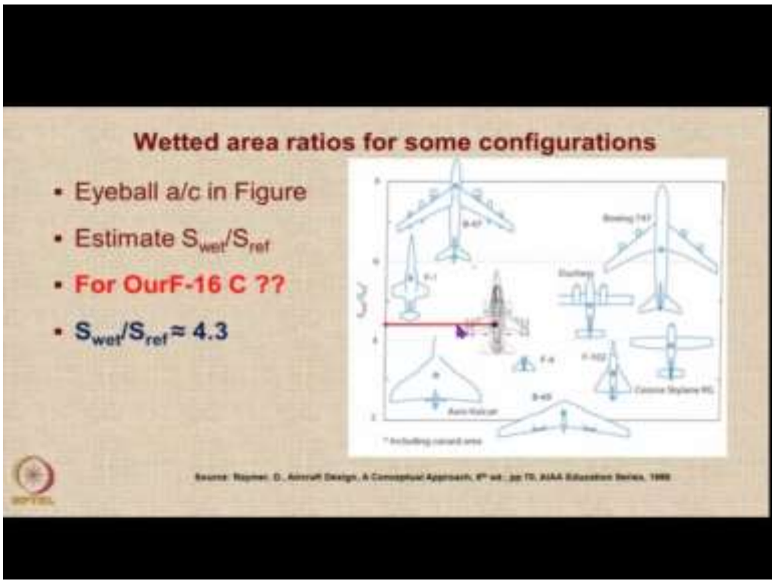

Let us get the wetted area ratios for our aircraft, for that we look at the value given in some configurations based on the general geometrical. So you eyeball the aircraft in the figure. And then after you eyeball the Aircraft, you estimate the wetted area ratio $\frac{S_{wet}}{S_{ref}}$. So, where does Our F 16 fit into this particular landscape. So if you notice, it is actually somewhere in between F 4 and F 104 in the shape. So it will come somewhere here, it will fit somewhere here. And if you actually proceed with eyeballing in that particular location, you get a $\frac{S_{wet}}{S_{ref}} = 4.3$.

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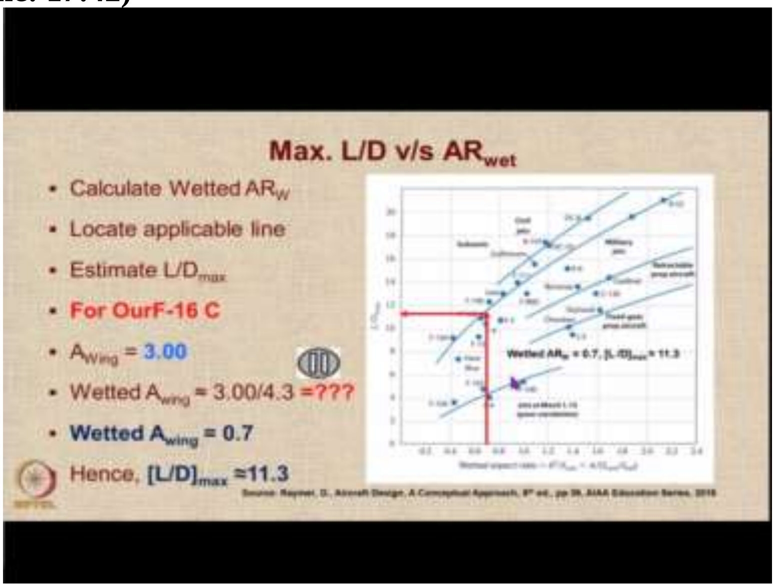

So, in our case, we will assume the $\frac{S_{wet}}{S_{ref}} = 4.3$. Now, this graph from Raymers textbook shows the value of L/D that can be L/D max that can be expected for various wetted aspect ratio values for various aircraft. So our aircraft is a military jet. So, what we do is we calculate the wetted aspect ratio, and then we locate the applicable line for our case, and then we just proceed from the x axis to the line and then we go to the y axis.

So, for Our F 16 aircraft, let us see, the A wing is known to be as 3, the aspect ratio of the wing is known to be 3 and therefore, the wetted aspect ratio of the wing will be 3 upon 4.3. At this point, I would request you to pause the video and calculate this number. The ratio comes out to be 0.7. So, if the wetted aspect ratio of the wing is 0.7 that will be somewhere here. So, you start somewhere here and go on the line for jet fighters military jets, you come on the x axis, you get the value of L/D max as approximately 11.3. So since our wetted aspect ratio is 0.7, as per this graph, the value of L/D max is approximately 11.3.

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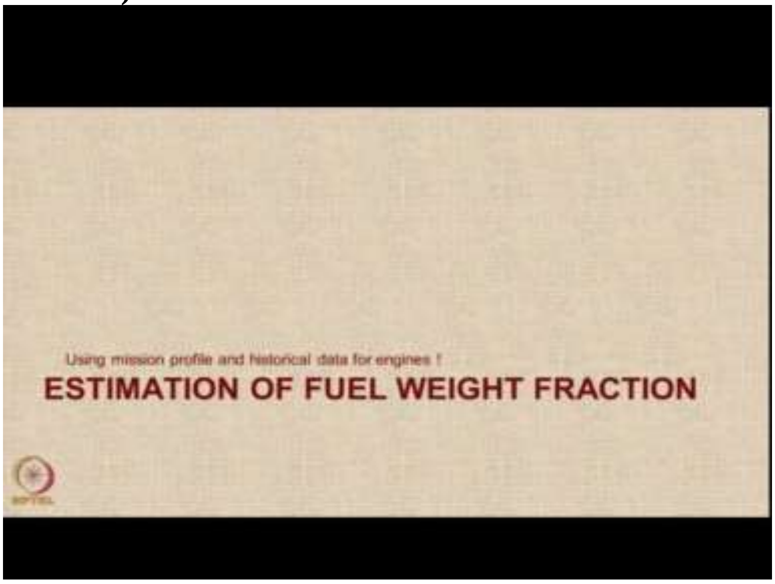

Let us now estimate the fuel weight fraction using mission profile and historical data for the engines.

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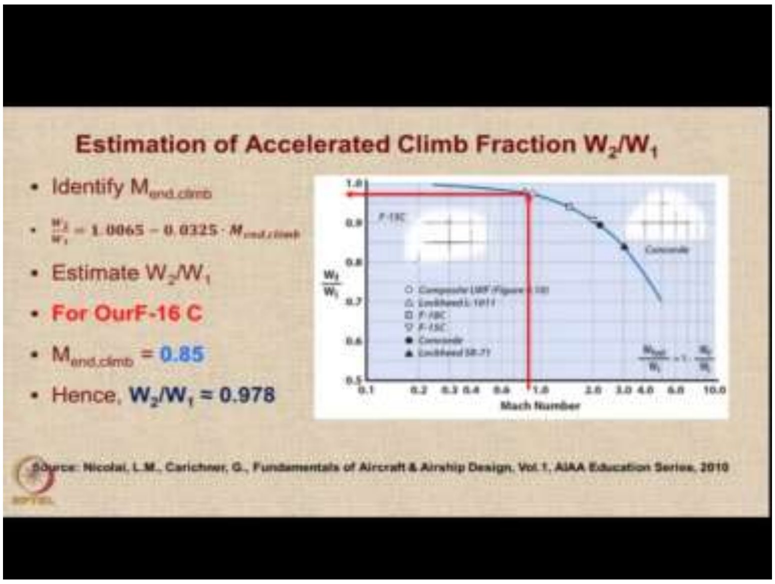

So, what you do is for the accelerated climb, which is the first one you identify the mach number at the end of the climb and then use this expression given by Raymer in his textbook to calculate the weight ratio. So, for Our F 16 aircraft, M end climb has been given as 0.85, because that is the beginning of the cruise. So, in this particular chart taken from the textbook by Nicolai and Carichner, you start with the M mach number of 0.85 go to the line and get the value of the weight ratio for climb. This number turns out to be 0.978.

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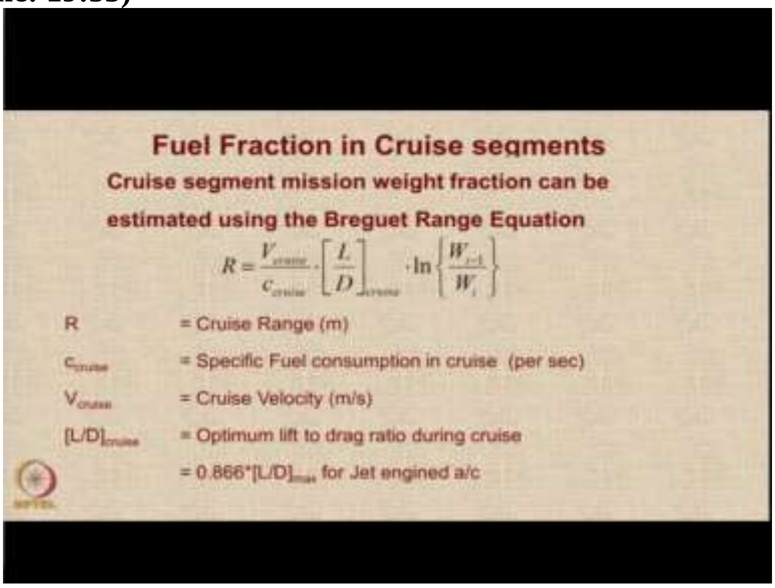

Let us look at the fuel fraction estimation in cruise segments. We can do it using the Breguet range equation

$$R = \frac{V}{c}\frac{L}{D}\ln\frac{W_{i-1}}{W_i}$$

And where as you are aware, this is already something which has been used in the past, so I am sure you would remember, we have already used this expression for the Boeing 787 sizing.

L/D has to be used as 0.866 times L/D max. And V_{cruise}, c_{cruise}. c_{cruise} the SFC which is already given V_{cruise} has to be estimated based on the mach number and the operating conditions.

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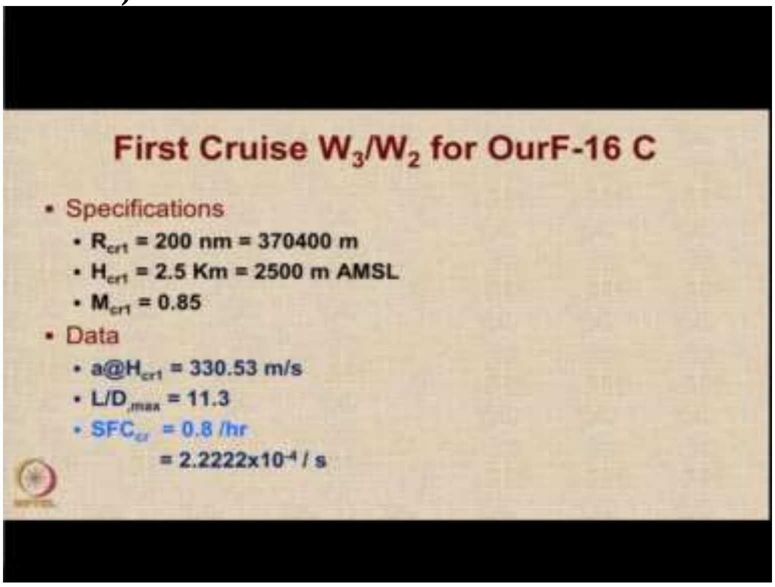

So for the first cruise of Our F 16 C aircraft, we have been given that the cruise range is 200 nautical miles, the cruise altitude is 2.5 kilometers and mach is 0.85, this is the specification. So that is why it is shown in the black color. The data is that the value of sonic speed at this altitude from the tables or by calculation is 330.53 at 1 kilometer above mean sea level, L/D max we have already obtained as 11.3, SFC cruise we have assumed to be 0.8 per hour. So to convert it into seconds for matching the units, we just divide this by 3600 and you get this value in seconds.

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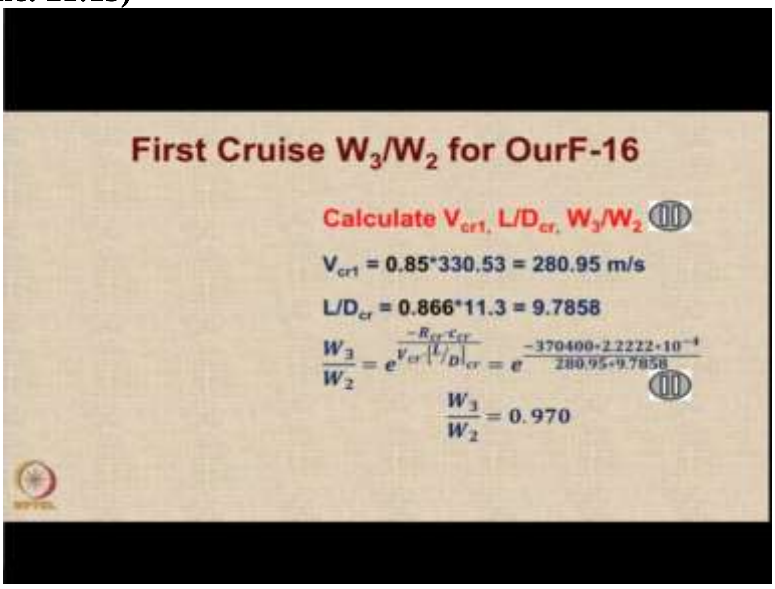

So, now I think we should, we have enough data to calculate the values of the cruise velocity, L/D cruise, and the weight ratio in the cruise. So at this stage, I would request you to pause the video and do these calculations. Let us see the values. So the cruise speed is 0.85 specified the Mach number into 330.53 that is 280.95. The L/D will be 0.866 times 11.3 which is the maximum L/D that is 9.7858.

And using this particular expression now we can calculate the value of the weight ratio. So I would request you to pause the video and do this calculation where R is this number in meters, this is in per meter. So, the units of the numerator are dimensionless on the bottom meter per second. So, this is in meter per second that means the units are our velocity. In the denominator we have velocity in meter per second and L/D is dimensionless. So, the units cancel out and we get just a ratio. So please pause the video and do this calculation. It comes out to be 0.970.

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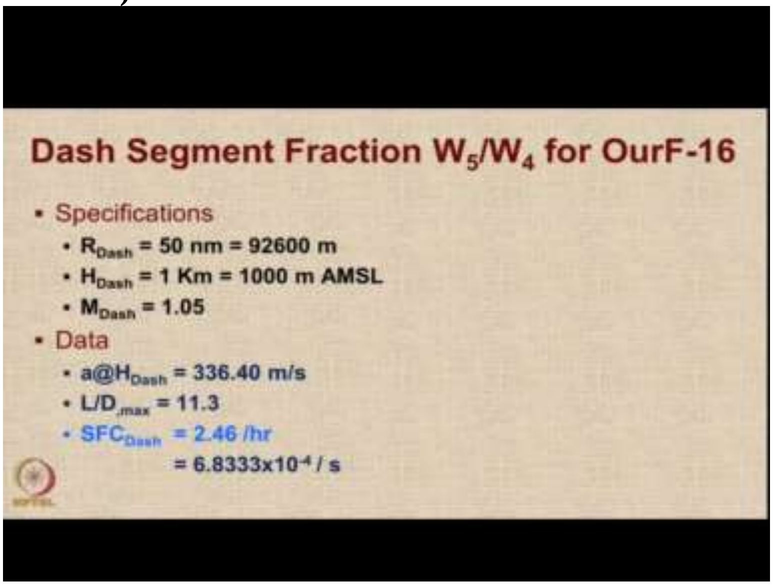

The dash segment is a segment in which we are going to travel just 50 nautical miles, 92.6 kilometers, but it is going to be at a supersonic mach number of 1.05. So under this condition, of course, the value of a can be calculated this is almost known to us the L/D max is 11.3 and SFC you will notice is 3, more than 3 times that of the cruise. So keeping these numbers in mind,

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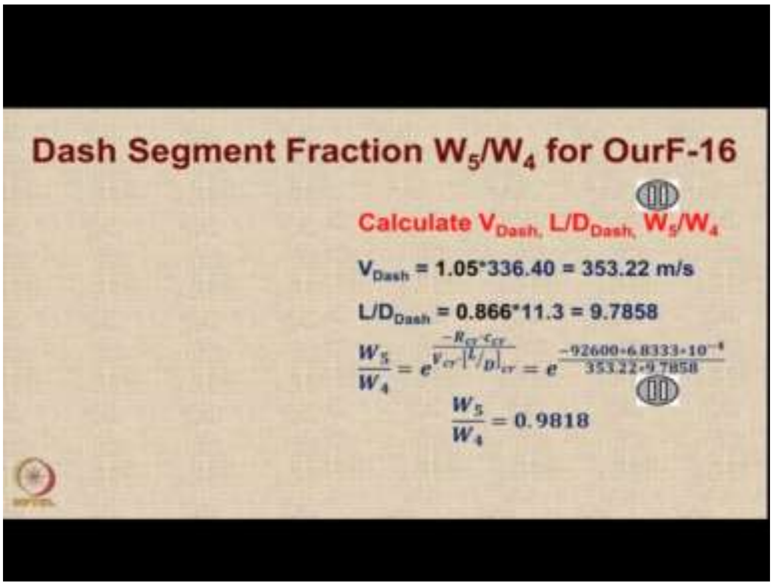

let us calculate now the value of V_{dash}, L/D dash and the weight ratio. So, I would like you to pause the video and do the calculation. V_{dash} will be simply mach number into sonic speed. Remember there is a slight difference because we are assuming conditions to be changing. It is not just ISA conditions. L/D dash will be again it is a cruise, so it will be 0.866 times L/D max and for the weight ratio we will have a formula.

So V_{dash} is 1.05 times 336.4 which is 353.22 meters per second. L/D dash is same because it is just 0.866 times L/D max. So putting these numbers in the expression you get these value and I would now request you to pause the video and do the calculation to calculate the ratio during the dash segment. So that ratio comes out to be 0.9818.

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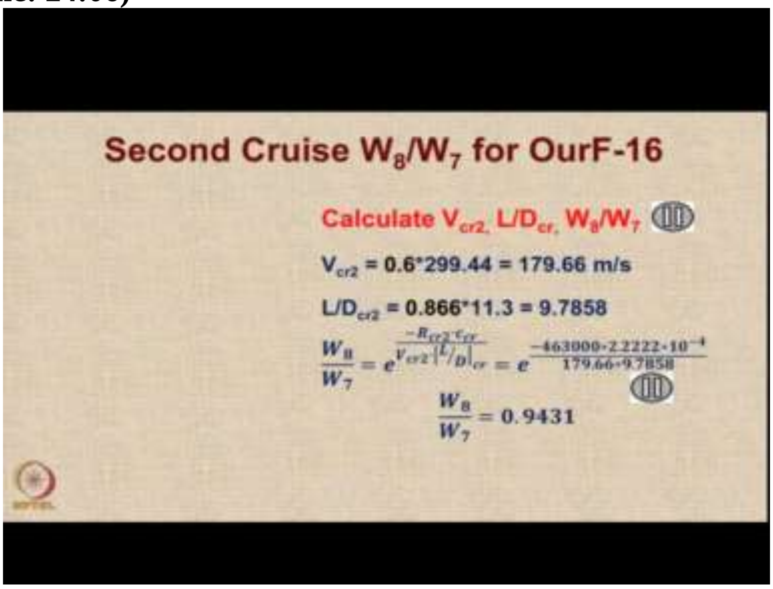

Moving ahead, let us look at the second cruise segment which will come later but since we are already in the cruise I thought we will do the cruise calculations together. This is the return cruise so the total distance is 250 nautical miles, the altitude is 10 kilometers and the mach number is 0.6. Therefore if you look at the tables you will get the value of speed of sound at this 10 kilometer altitude, L/D max will remain the same, and SFC also will remain the same because we are at a low mach number cruise without any afterburner.

At this stage I would like you to pause the video and calculate the value of V_{cr2} and L/D cruise. And later on we will get an expression for $\frac{W_8}{W_7}$ the weight ratio in the second cruise. So V_{cr2} will be 0.6 times 299.44 which is 179.66 meter per second, L/D cruise will remain the same. For calculating the weight ratio, we need to insert the numbers of range, the SFC, the velocity and the L/D in this expression. I would like you to pause the video and do this calculation. The number comes out to be 0.9431.

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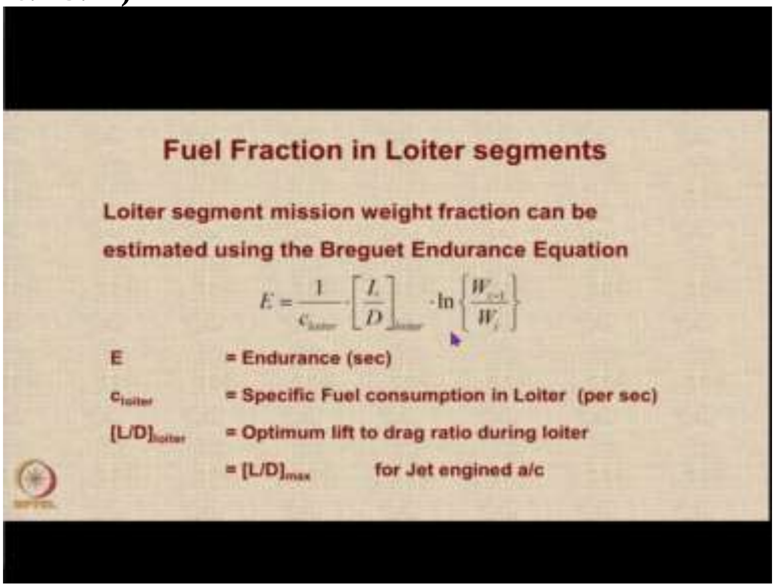

Now, we go to the 2 loiter segments, again you can use the Breguet endurance equation, but here the c will be the c for loiter which is in this case given us slightly more than that for cruise and L/D loiter was going to be L/D max because it is a jet engine aircraft and we know that jet engine aircraft obtains its max endurance when it flies at a speed corresponding to L/D max.

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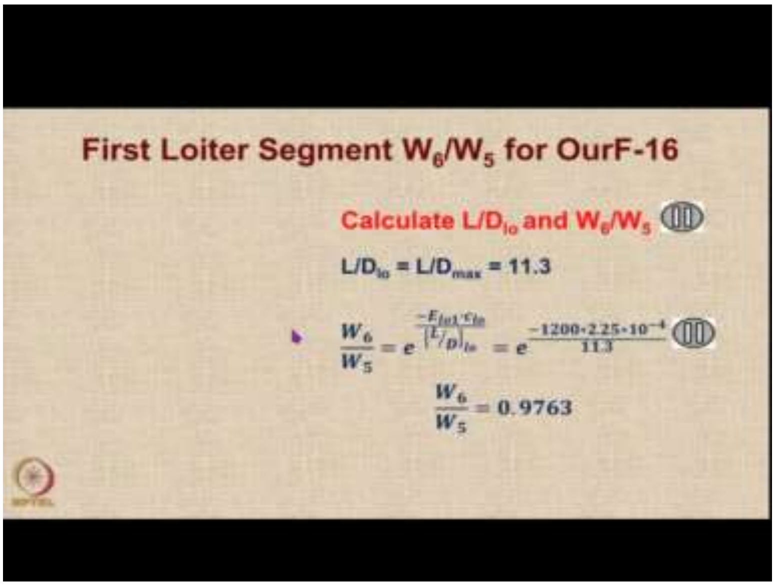

So, for the first loiter segment for Our F 16 aircraft, we have the requirement of 20 minutes of endurance which is 1200 seconds, the data is L/D max is 11.3, SFC is given as 0.81 per hour. And now we can calculate L/D during loiter and the weight ratio. The L/D is going to be the same as L/D max as I already mentioned, and for the weight ratios, we just have to do the calculation using this expression. Pause the video and do the calculations please. We get the weight ratio is 0.9763.

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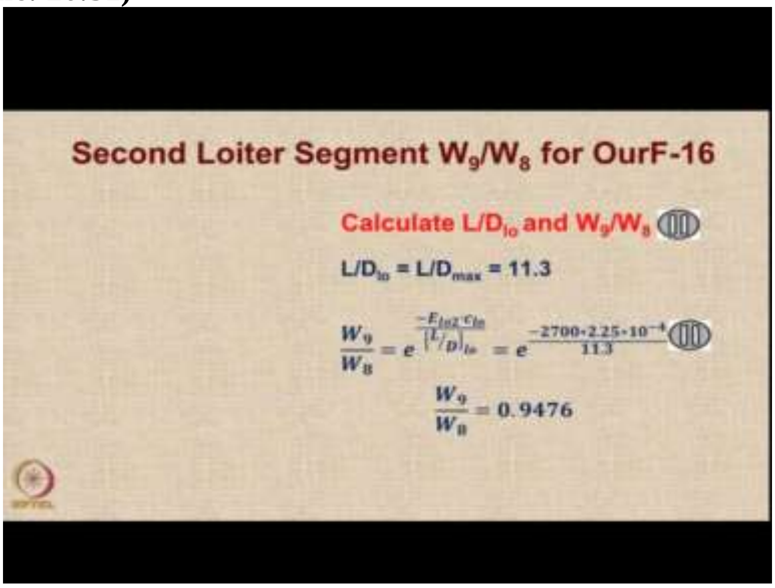

And then we have the second loiter segment which occurs for 45 minutes, for this the data is the same. And the L/D also is going to be the same, L/D max, we just need to do the calculation by putting in the correct value of the duration of our loiter in this expression. So this number, you can pause the video and do the calculation. The number turns out to be 0. 9476.

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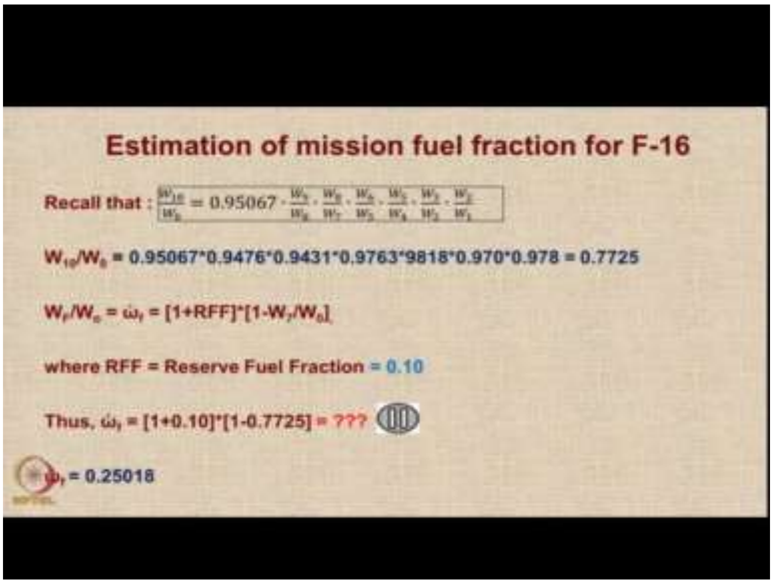

So, what we do now is we bring, we know that we had to calculate these 6 fractions. So we bring all the numbers together which we have calculated for the line, for the cruise and all the segments. And if you multiply all of them together, you get the expression as 0.7725. So if you now use this expression including the reserve fuel fraction of 10 %, you can get the value of

$$\frac{W_F}{W_0} = (1 + 0.1) * (1 - 0.7725)$$

Please pause the video and calculate this number. Turns out to be 0.25018. So nearly one fourth of the aircraft weight, slightly more than one fourth of the aircraft weight is going to be the fuel.

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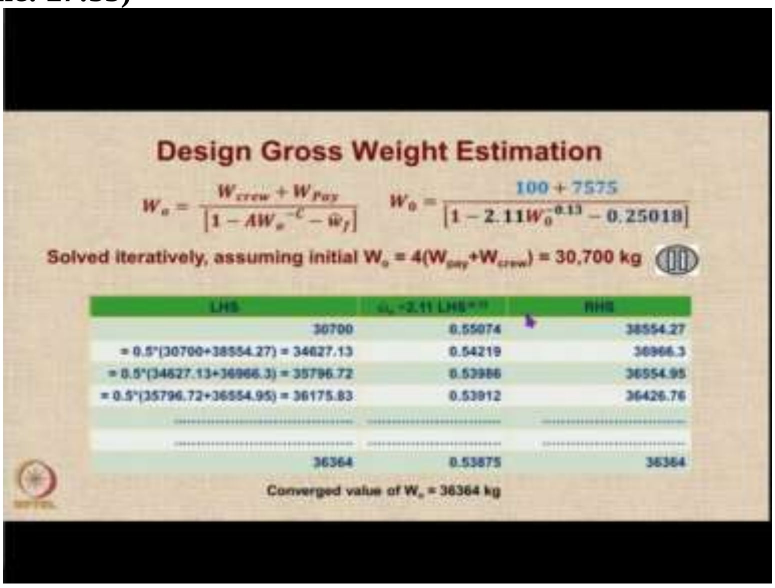

Now, let us go to, now our basic master equation of design gross weight estimation which is that

$$W_0 = \frac{W_{crew} + W_{pay}}{1 - AW_0^{-c} - \overline{w}_f}$$

Notice because this expression has W_0 on both LHS and RHS, it is going to be obtained in some iterative fashion.

So what we do is they plugin in this the value is known to us crew is known to us 100 kilograms, pilot plus g suit et cetera, payload is given as 7575, A is 2.11 and C is minus 0.13 for a fighter aircraft. And to the fuel weight fraction we have just estimated. So what we do is we solve it iteratively by assuming the LHS to be 4 times the numerator that is 30700. This is just a hint. So I would request you to now pause the video.

Start with the assumed value as 3700 calculate the RHS value that is

$$W_0 = \frac{100 + 7575}{1 - 2.111W_0^{-0.13} - 0.25018}$$

Then whatever number you get, take that and 3700 together and get the mean of that number as the next trial, and so on and so forth till you get a converged solution. So I am going to request you to pause the video at this stage and do this calculation because unless you do calculations you don't actually appreciate aircraft conceptual design.

So we start with 3700 and we get the empty weight fraction as 0.55074 the RHS is 38554.27. In the next iteration, the number on the LHS would be the average of these 2 numbers, 34627 using that if you calculate the value of empty weight fraction you get some number and then you get this number. Still there is a difference of around 2000 or more. So, you take the next value as the average of these 2 numbers.

Like that you keep on doing till these 2 numbers slowly converge to each other. So the third trial would be take this number as 36554.7 plus the previous number half of that 36175. And notice now, you are slowly converging, the left, LHS value is 36176 RHS is 36426 difference is only about 200. Keep on doing the iterations once, twice, thrice, 3 4 times, ultimately, you will achieve a converge value of 36364, for which the empty weight fraction would be 0.53875.

Hence, the converge value of the gross weight is 36364 kg. The aircraft is going to weigh approximately 36 tonnes. Notice how this value is not very far away from the originally assumed value of approximately 4 times the payload and crew members.

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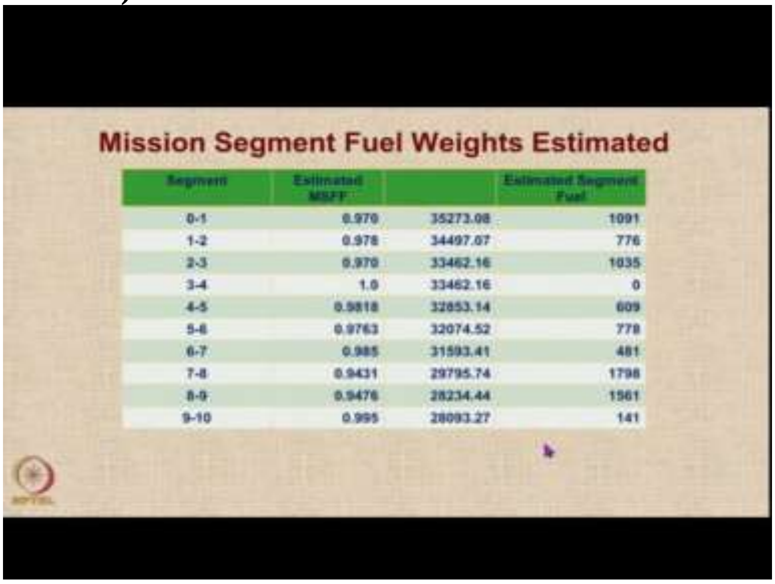

Mission Segment Fuel Weights Estimated

Segment	Estimated MSFF		Estimated Segment Fuel
0-1	0.970	35273.08	1091
1-2	0.978	34497.07	776
2-3	0.970	33462.16	1035
3-4	1.0	33462.16	0
4-5	0.9818	32853.14	609
5-6	0.9763	32074.52	778
6-7	0.985	31593.41	481
7-8	0.9431	29795.74	1798
8-9	0.9476	28234.44	1561
9-10	0.995	28093.27	141

Let us have a look at what is the amount of fuel consumed in each segment, because we have done the segmental calculation, so in the first segment, which is the warm up taxi out and take off, around a 1091 kilograms of fuel is gone. This is actually an over estimate as we saw last time also, this number is normally very small. But for a military aircraft actually, you might end up actually spending a large amount of fuel in warm up and taxi out.

Because you do have to spend a lot of time on the ground testing your systems before you actually go for a mission. The next segment is the climb segment for that the fuel weight fraction is 0.978. This is a accelerated climb to 2.5 kilometer unlike a normal climb where this number is 0.985, this is 0.978. So, quite a good amount of fuel has been consumed. The next is the cruise segment where you have consumed 1000 kg.

So notice the fuel consumed in the initial segment of warm up taxi out and take off is actually more than that in the first cruise segment as in this case, the next segment is the descent segment in which we actually ignore the mission fuel so therefore it is 0. After that we have small segment where we had a dash. And after, we had a loiter first, we had a dash and then a loiter.

So you can see that the amount of fuel consumed in both of them is almost similar. After that we had a climb and this was a very comfortable climb to 10 kilometer. So unlike the first climb where we consumed 776 kilograms, we are only consumed 481 kilograms here although we are going to 10 kilometers from the almost, it is almost the ground level value or 1 kilometer altitude that is because it is un accelerated.

The next cruise is happening at for 250 nautical miles. So, you can notice that the fuel consumed is here is the largest. This was the fuel consumed the first cruise. This is the fuel consumed in the second cruise. Then you have the loiter segment which consumes 1561 kgs, because you are loitering for 45 minutes at this place. And then finally, you are coming into land and when you are coming into land.

So, we see that the return cruise and the return loiter in this case have the highest fuel consumption followed by the cruise segment and the warm up segment. The segments of dash and loiter of 20 minutes are not consuming that much fuel.

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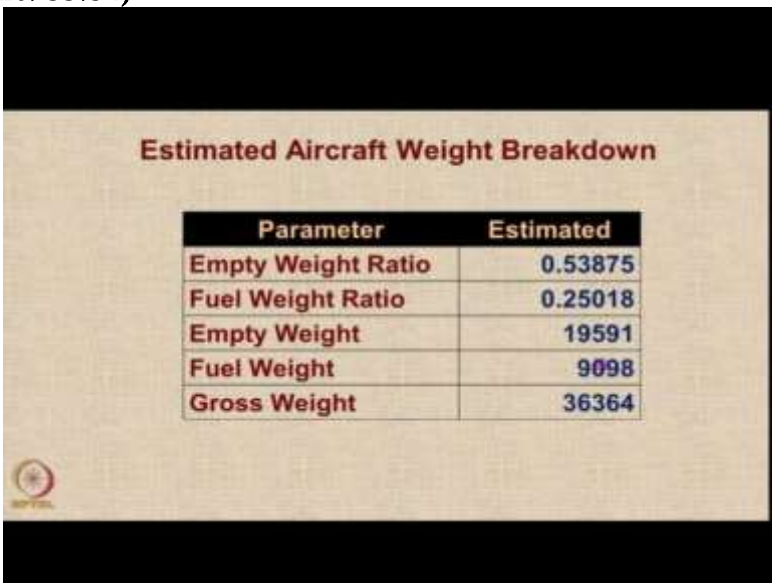
Estimated Aircraft Weight Breakdown

Parameter	Estimated
Empty Weight Ratio	0.53875
Fuel Weight Ratio	0.25018
Empty Weight	19591
Fuel Weight	9098
Gross Weight	36364

So with these numbers, let us see what is the weight breakdown that we got. So the empty weight ratio we got was 0.53875. So nearly half the aircraft is empty weight slightly more than that. The fuel weight ratio we got is 0.25, which means almost quarter of the aircraft. The empty weight we got is 19591 kgs. This number is not very far from the F 16 aircraft. Although as I mentioned, the fuel weight for F 16 is very less. It is only about I think 3000 kilograms, but here it is 9000 because we are expecting the aircraft to do many, much bigger mission and much more loiter here. And the gross weight we get is 36364 kg.

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So I would like to acknowledge the contribution of these 4 authors with their very interesting textbook from where I have taken some basic data for Our F 16 C aircraft. Daniel Raymer needs to be thanked for his extremely popular and seminal textbook on aircraft design. I have also like to thank Leyland Nicolai and Grant Carichner for their excellent book, textbook on updated data on the large database. From where I have taken a couple of graphs from their book for calculations. And last but not the least, I want to thank my teaching assistant Nouman Uddin for help in creating this tutorial. Thank you so much.