Introduction to Aircraft Design

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Lecture - 51
Component Buildup Method

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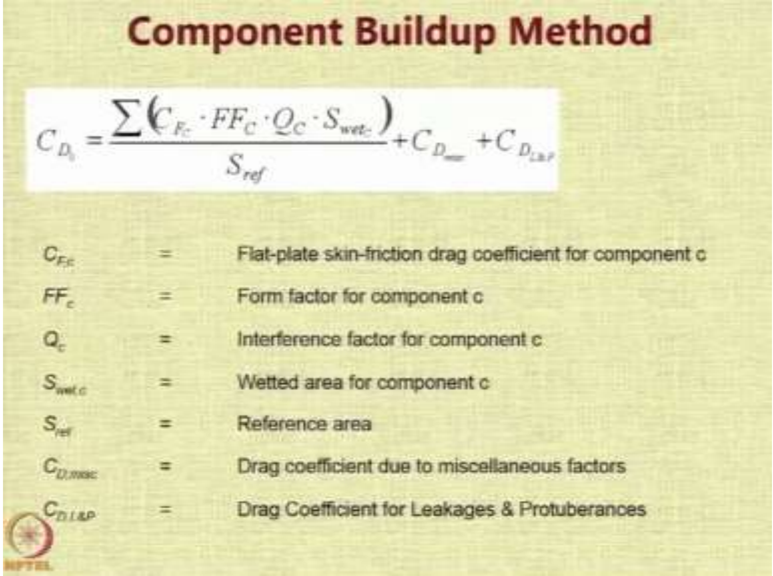

Component Buildup Method

$$C_{D_0} = \frac{\sum (C_{F_c} \cdot FF_C \cdot Q_C \cdot S_{wet_c})}{S_{ref}} + C_{D_{misc}} + C_{D_{L\&P}}$$

C_{F_c} = Flat-plate skin-friction drag coefficient for component c
FF_c = Form factor for component c
Q_c = Interference factor for component c
$S_{wet\,c}$ = Wetted area for component c
S_{ref} = Reference area
$C_{D,misc}$ = Drag coefficient due to miscellaneous factors
$C_{D\,L\&P}$ = Drag Coefficient for Leakages & Protuberances

So, the general formula for the component buildup method is as shown here,

$$C_{D_0} = \frac{\sum C_{f_c} * FF_c * Q_c * S_{wet_c}}{S_{ref}} + C_{D_{misc}} + C_{D_{L\&P}}$$

where the various components or various terms in the equation are as described.

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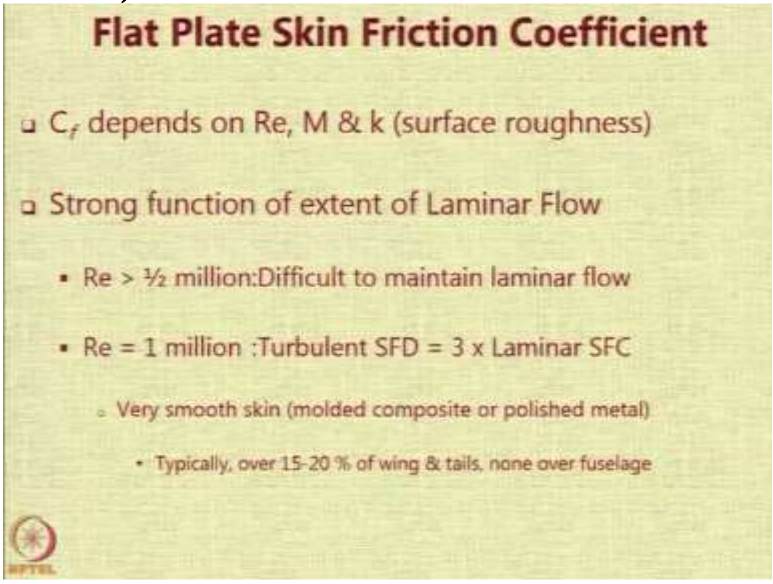

Flat Plate Skin Friction Coefficient

- C_f depends on Re, M & k (surface roughness)
- Strong function of extent of Laminar Flow
  - Re > ½ million:Difficult to maintain laminar flow
  - Re = 1 million :Turbulent SFD = 3 x Laminar SFC
    - Very smooth skin (molded composite or polished metal)
      - Typically, over 15-20 % of wing & tails, none over fuselage

So, how do you estimate the flat plate skin friction coefficient this depends on the Reynolds number, the Mach number and the surface roughness and it is a very strong function of the extent of laminar flow, if you have laminar flow over the entire body, then the value of C_f will be quite low. And if you have turbulent flow over the whole body, then it will be much larger. Now, experience has shown that, when you have a Reynolds number more than half a million, it is very difficult for you to maintain laminar flow.

And at a Reynolds number of 1 million, the turbulent skin friction drag is 3 times the laminar of skin friction drag. So, if you are able to use very smooth skin using a polished metal or using a molded composite, then you might be able to maintain laminar flow over around 15 to 20% of the wings and the tails, but on the fuselage, it is very difficult to maintain laminar flow, maybe 5% of the fuselage perhaps may have maybe not.

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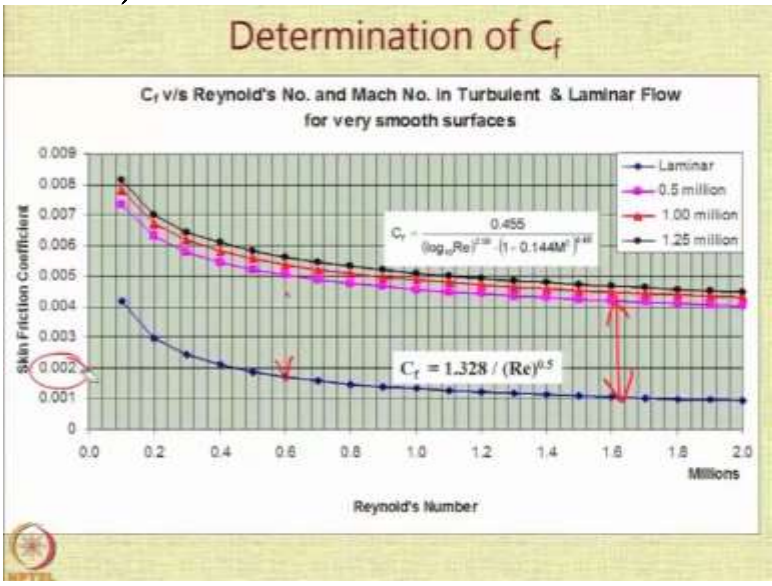

Determination of C_f

This particular graph shows the variation of the C_f value skin friction coefficient as a function of Reynolds number for laminar flow shown in the blue line so, this line is for laminar flow. And these 3 lines are for the turbulent flow, because the formulae are a little bit different for the 2. Now, what we notice is that the gap between the skin friction coefficient for fully laminar flow and turbulent flow is quite huge.

And in a simple, you know, typically this is going to be nearly one third. So, if you notice here, for example, if you look at the Reynolds number of around 0.4 million, you know you have 0.002 and 0.006. So, it is a factor of 3, it is one third and this is a huge saving. So if you can maintain laminar flow, it is a very big but if you can, then you have a chance of reducing the laminar flow to a value of nearly one third.

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Piaggio P-180 Avanti
Twin turboprop executive transport

Three Surface Aircraft

V_{max} 400 kt, V_{cr} 350 kt

Laminar Flow over 50% of wing & tail and 35 % of fuselage

NLF wing designed by Ohio University

And this is the reason why many attempts are made to maintain laminar flow. The Piaggio Avanti aircraft is 1 example of a 3 surface aircraft, where the designers have provided special features in the aircraft to ensure that there is a laminar flow of nearly 50% of the wing and one third of the fuselage and for this aircraft a very special NLF wing was designed by the Ohio University.

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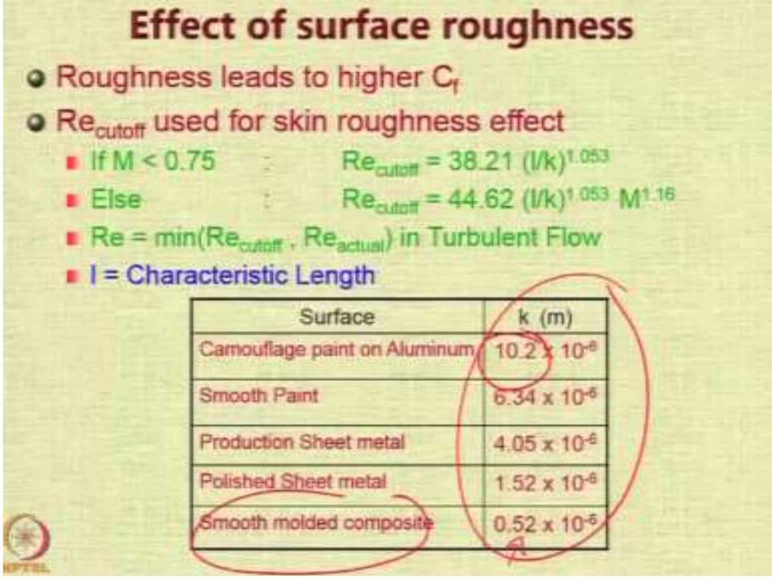

Effect of surface roughness

- Roughness leads to higher C_f
- Re_{cutoff} used for skin roughness effect
  - If M < 0.75 : $Re_{cutoff} = 38.21\ (l/k)^{1.053}$
  - Else : $Re_{cutoff} = 44.62\ (l/k)^{1.053}\ M^{1.16}$
  - $Re = \min(Re_{cutoff}, Re_{actual})$ in Turbulent Flow
  - l = Characteristic Length

Surface	k (m)
Camouflage paint on Aluminum	10.2×10^{-6}
Smooth Paint	6.34×10^{-6}
Production Sheet metal	4.05×10^{-6}
Polished Sheet metal	1.52×10^{-6}
Smooth molded composite	0.52×10^{-6}

The second point that is important is that surface roughness leads to higher value of the skin friction coefficient. So, to take care of the effect of surface roughness, what we do is we use the concept of Re cutoff, cutoff Reynolds number. So, if the Mach number is less than 0.75, then we define the cutoff Reynolds number in terms of l over k where l is the characteristic length of the component and k is the surface roughness.

So, if you notice what we do is we use the value of either the cutoff Reynolds number or the actual Reynolds number in the turbulent flow calculation. So, if you go back and have a look at the formula for the turbulent flow, you can see that the Reynolds number comes in the denominator and the power is 2.58. So, if Reynolds number is large, then the value of C_f is going to be small. But, if we have surface roughness, or if we have more surface roughness, then what we do is instead of the actual Reynolds number.

We use a cutoff Reynolds number which is a larger value a smaller value sorry and the smaller value gives you a higher value of C_f and this is how you take care of the effect of surface roughness. So, what you do is, you calculate the cutoff Reynolds number and if you find that the cutoff Reynolds number is lower than the actual Reynolds number, you use that number in the formula given on the previous slide and you will get the required C_f value.

If you do not know the value of surface roughness, some characteristic values are given here for typical types of surface that is provided you can notice that the lowest value of surface roughness is for the smooth molded composite, the value is just in a $0.52*10^{-6}$ whereas, a camouflage paint on aluminum has nearly 20 times more. So, you can see that the surface roughness is going to make a huge difference in the calculation of the C_f.

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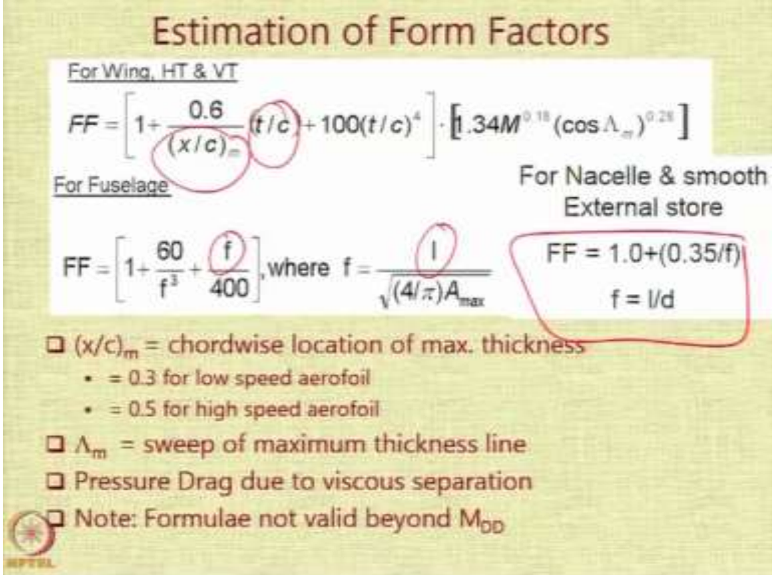

Estimation of Form Factors

For Wing, HT & VT

$$FF = \left[1 + \frac{0.6}{(x/c)_m}(t/c) + 100(t/c)^4\right] \cdot \left[1.34M^{0.18}(\cos\Lambda_m)^{0.28}\right]$$

For Fuselage

$$FF = \left[1 + \frac{60}{f^3} + \frac{f}{400}\right], \text{where } f = \frac{l}{\sqrt{(4/\pi)A_{max}}}$$

For Nacelle & smooth External store

$FF = 1.0+(0.35/f)$

$f = l/d$

- ☐ $(x/c)_m$ = chordwise location of max. thickness
  - = 0.3 for low speed aerofoil
  - = 0.5 for high speed aerofoil
- ☐ Λ_m = sweep of maximum thickness line
- ☐ Pressure Drag due to viscous separation
- ☐ Note: Formulae not valid beyond M_{DD}

Now, to get the value of form factor, because form factor FF is to be multiplied with the value of in the calculation of the skin friction coefficient. So, for bodies which are like a wing, horizontal tail or vertical tail lifting surfaces, this formula in terms of the maximum location of the x/c or location of the maximum thickness and the t/ c thickness to chord ratio and the sweep at the quarter chord and the Mach number these 4 parameters the sweep, Mach number the t/c and the location these 4 parameters decide the value of the form factor.

So, this $(x/c)_m$ is the location $(x/c)_m$ is shown here, that is the location of the maximum thickness if we do not know you can take it as 0.3 for low speed airfoils or 0.5 for high speed airfoils, lambda m is the sweep of the maximum chord line, maximum thickness line sorry. And, you know, if you do not know the value, you can get this value by the simple formulae the form factor for bodies like a fuselage or nacelle which are round, which are bodies that have some diameter is obtained using this particular formula.

Here we use the factor small f, where small f is

$$f = \frac{l}{\sqrt{(4/\pi)A_{max}}}$$

where A_{max} is the maximum cross sectional area if we have a nacelle or a smooth store, then we can use this formula where f = l/d, l stands for the characteristic length. Now, formulae are not to be used beyond the Mach M_{DD} Mach drag divergence Mach number.

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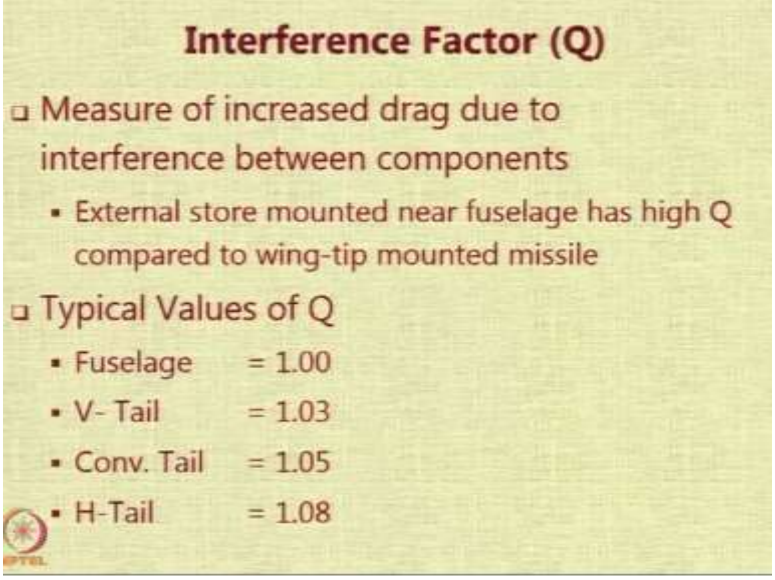

Interference Factor (Q)

- Measure of increased drag due to interference between components
  - External store mounted near fuselage has high Q compared to wing-tip mounted missile
- Typical Values of Q
  - Fuselage = 1.00
  - V- Tail = 1.03
  - Conv. Tail = 1.05
  - H-Tail = 1.08

They have to be used only for subsonic flow calculations. And then we look at the interference factors Q. This is a measure of what is the effect of the presence of a component to the component nearby. And, if you have an external store such as a bomb or a rocket or a drop tank or any other item suspended below the aircraft, if you mount it near the fuselage, it has got a very high value of Q compared to something that you mount near the wingtip because you move far and far away.

So, with the fuselage as a baseline the value of Q will be 1.0. And for various types of tail, V tail, conventional tail, H tail you can see there are different values of Q which are recommended.

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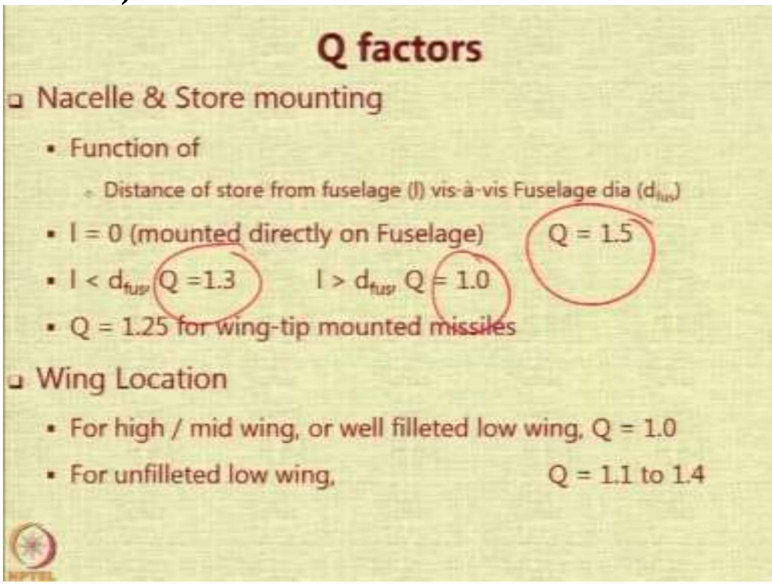

Q factors

- Nacelle & Store mounting
  - Function of
    - Distance of store from fuselage (l) vis-à-vis Fuselage dia (d_{fus})
  - l = 0 (mounted directly on Fuselage) Q = 1.5
  - l < d_{fus}, Q =1.3 l > d_{fus}, Q = 1.0
  - Q = 1.25 for wing-tip mounted missiles
- Wing Location
  - For high / mid wing, or well filleted low wing, Q = 1.0
  - For unfilleted low wing, Q = 1.1 to 1.4

Now, for nacelle and store mounting the value of Q factor is a function of how much distance you are from the fuselage vis-a-vis the fuselage diameter. So, if you mount it directly on the fuselage, then the distance of the store is 0 and Q is very high. In other words, it means that there is a 50% increase in drag because of interference. If you mount it in such a way that the location is less than 1 diameter of the fuselage, then it becomes 30% higher or 1.3.

And if you clear the distance equivalent to the fuselage diameter, then the Q value equal to 1 which practically means no interference. For wingtip mounted missiles, we use Q as 1.25. If you have a high or a mid-wing or if you have a well filleted low wing, then we assume there is hardly any interference but if you have an unfilleted low wing you can have it between 1.1 to 1.4.

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Leakage & Protuberance Drag

- Leakage
  - Tendency to "inhale/exhale air through holes"
- Protuberances
  - Antennae, lights, door edges, fuel vents, protruding rivets,..
- Estimated as a % of total parasite drag coefficient.
  - Bombers 02-05 %
  - Transport a/c / Turboprops 05-10 %
  - Fighters 10-15 %

Now, one more term to be considered is the leakage and protuberance drag. Now, what is meant by leakage? Leakage is the tendency of the aircraft to inhale or exhale the air through the various holes, every aircraft has got some scoops mounted so, that the ambient air can be used for cooling of the various devices or equipment inside. And from these at these places, basically the ambient air is brought to rest and hence, there is going to be a loss of momentum which will correspond to a drag.

There are protuberances on every aircraft there are antennae, there are lights, there are edges of the doors, there are fuel vents there are in sometimes there are rivets, which are protruding all of these are going to contribute to additional drag which we call as the protuberance drag. So, here what is done normally is a percentage is taken. So, you look at historical information and you assume that bombers will have approximately 2 to 5% additional parasite drag because of protuberances transport.

And turboprops will have larger values of 5 to10% but the fighter which will have many, many appendices and drop tanks and armaments, etc, protruding out they are going to have much larger values say between 10 to 15%.

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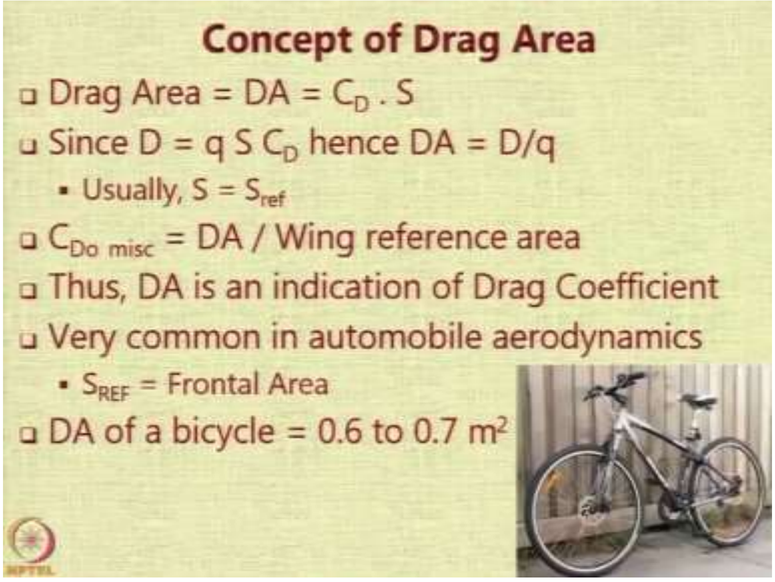

Concept of Drag Area

- Drag Area = DA = C_D . S
- Since D = q S C_D hence DA = D/q
  - Usually, S = S_{ref}
- $C_{Do\ misc}$ = DA / Wing reference area
- Thus, DA is an indication of Drag Coefficient
- Very common in automobile aerodynamics
  - S_{REF} = Frontal Area
- DA of a bicycle = 0.6 to 0.7 m^2

Let us have a look at the concept of drag area to take care of the drag of miscellaneous items. So, drag area is defined as the product of the drag coefficient created by attributed to the particular body or a particular component multiply by its area. So, since drag is

$$D = qSC_D$$

therefore, drag area can be called as D/q because D/q will have the same numerical value as SC_D. So, sometimes we also refer drag area is as D/q value.

So, usually we use S as S_{ref}. So, the miscellaneous drag coefficient C_{D_0} will be the drag area divided by the wing reference area. And what you do is you keep you add the drag area of various components to get total drag area and if you when you divide that by the wing reference area, you will get the C_{D_0} miscellaneous. So therefore, drag area is a direct indication of the drag coefficient. And this concept is very commonly used in the automobile aerodynamics in which case the reference area is S_{ref} or the frontal area. So, for example a bicycle has a drag area of 0.6 to 0.7 square meters.

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DA of some cars

Model Name	Drag Area (m²)
Volkswagen XL1	0.279
Honda Insight	0.474
Hummer H2	2.46

Source: http://en.wikipedia.org/wiki/Automobile_drag_coefficient#Drag_area

Look at some cars so if you have a car like Volkswagen XL I and also notice the rear wheel is actually hidden in the covering you have a very low value of drag area. On the other hand a car like Honda inside which is fairly smooth and aerodynamically shaped will have but exposed the wheels will have you know nearly double the drag area. But if you look at a car like a Hummer which is having a very squarish front area and a very large it will have you know maybe nearly 10 times more drag area compared to a Volkswagen XL 1. So, it is very common to use this concept of drag area in automobile aerodynamics.

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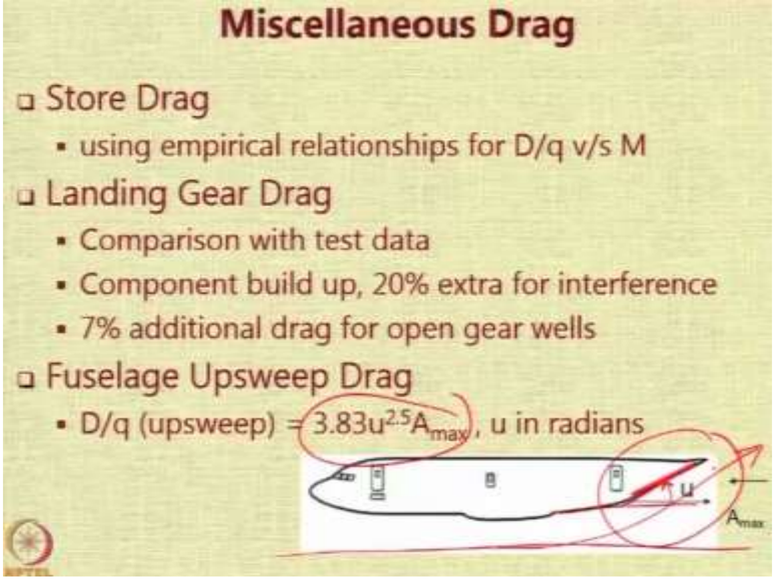

Miscellaneous Drag

- Store Drag
  - using empirical relationships for D/q v/s M
- Landing Gear Drag
  - Comparison with test data
  - Component build up, 20% extra for interference
  - 7% additional drag for open gear wells
- Fuselage Upsweep Drag
  - D/q (upsweep) = $3.83u^{2.5}A_{max}$, u in radians

So we can look at miscellaneous drags now, so drag of the stores. So, for estimating the drag of each store that is suspended below the aircraft you might use some empirical relationships given. So D/q versus Mach number curves are available for various stores and the store suppliers normally provide these curves. You can use them to get the value of D/q and then add it to the miscellaneous drag, for landing gear drag normally the values are estimated with a comparison from the test data.

So, what you do is you use a component build up method where each component of the landing gear is considered to be creating drag. So, you calculate drag of each and then you take 20% extra for interference between them, if you have open gear wells, you take 7% more drag. Now, one more cause of high drag is the fuselage upsweep which we see many a times in cargo transport aircraft.

So, in these aircraft, normally a door is mounted at this location. So, there has to be a very abrupt change in the angle. So, you have this upsweep angle u and there is a formula available for D/q of the upsweep even the value of using radians you can use this particular area and in this formula A max is supposed to be the area cross sectional area in this particular view.

So, with this you can estimate the value of the additional drag due to fuselage upsweep. So, what is happening here is that the air which is flowing past the aircraft is suddenly made to turn up. And this upward motion of air causes this additional drag called the fuselage upswept drag.

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Flap and Speed Brake Drag

- Flap Drag
  - $\Delta C_{Do\ flap} \cong F_{flap} (C_f/C) (S_{flapped}/S_{ref}) (\delta_{flap} - 10)$
  - $F_{flap} = 0.0144$ for plain flaps
  - $F_{flap} = 0.0074$ for slotted flaps
  - $\delta_{flap} = 20 - 40°$ @ Takeoff
  - $\delta_{flap} = 60 - 70°$ @ Landing
- Speed brake drag
  - $\Delta C_{Do} \cong 1.0$ to 1.6* speed brake frontal area

Flaps and the speed brakes are also huge components, huge contributors to the drag flap drag is estimated by a factor called F flap that is a function of the type of the flap, flap chord ratio this is the extent of the flap, flapped area / S_{ref} area is also the extent of the flap along the span and delta flap is the flap angle, we assume that up to 10 degrees of angle the contribution is very, very minor so, it can be ignored.

So, only deflections beyond 10 degrees are assumed to contribute to the additional drag this particular figure indicates what is meant by the flapped area S_{flapped} as mentioned here. So, the flapped area is not just the area covered by the flaps, but the area which is under the area of the aircraft which is either ahead or behind the flaps. So, the area that is under the influence of the flaps is called as a flapped area.

So, F_{flap} there are various so, each of the type of flaps there are separate values suggested for the F_{flap}. So, it is like a small value for plane flaps smaller value for slotted flaps, because they are more efficient, delta flap is normally specified but if not you have to assume a value from historical information, speed brakes are also going to create a huge amount of drag because they are almost like flat plates which come out and project. So, you can assume delta C_{D_0} to the flat plates to be nearly 1 to 1.6 times the speed break for frontal area.

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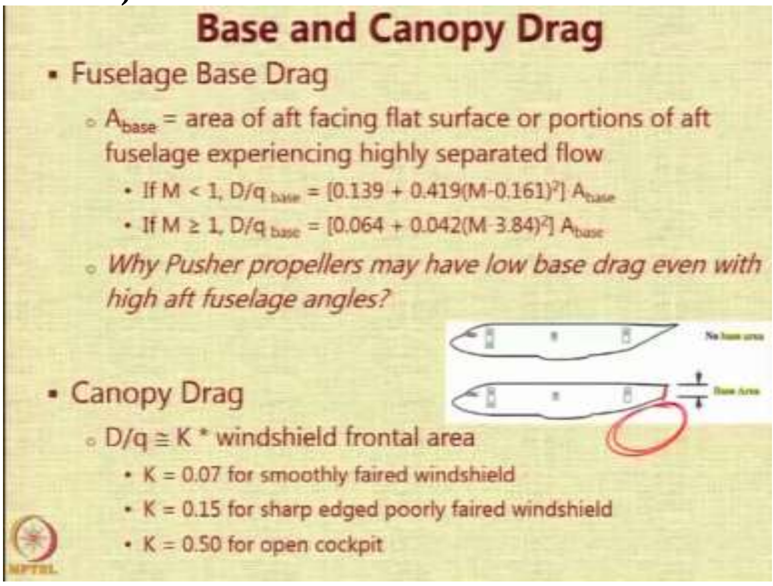

Base and Canopy Drag

- Fuselage Base Drag
  - A_{base} = area of aft facing flat surface or portions of aft fuselage experiencing highly separated flow
    - If M < 1, $D/q_{\,base} = [0.139 + 0.419(M-0.161)^2]\,A_{base}$
    - If M ≥ 1, $D/q_{\,base} = [0.064 + 0.042(M-3.84)^2]\,A_{base}$
  - *Why Pusher propellers may have low base drag even with high aft fuselage angles?*
- Canopy Drag
  - $D/q \cong K$ * windshield frontal area
    - K = 0.07 for smoothly faired windshield
    - K = 0.15 for sharp edged poorly faired windshield
    - K = 0.50 for open cockpit

And then you have the base and canopy drag in many aircraft, the edge of the tip of the fuselage is not closed, but there is a base and because of this there is a abrupt disturbance in the flow. So, this leads to separated flow and hence there will be additional drag because of this and there are formulae available for calculating the value of the D/q of the base as a function essentially of the base area, which is again this is the base area, the area that you encounter on the base of the aircraft.

So, you can have a query in mind that pusher propellers may have low base drag even with high aft fuselage angles and also with the large base areas. The reason for that is that the flow in the area flow in this particular area is manipulated by the presence of propellers in the pusher aircraft. Canopy is also a huge contributor of drag sometimes depending on its shape, whether it is flat or whether it is curved, depending on how it is located.

So, depending on how the canopy is you can create you can assume the value of K and get the value of ${}^{D}\!/_{q}$ as a function of the windshield frontal area. Thanks for your attention we will now move to the next section.