Introduction to Flight
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Lecture 06.2
Wave Drag

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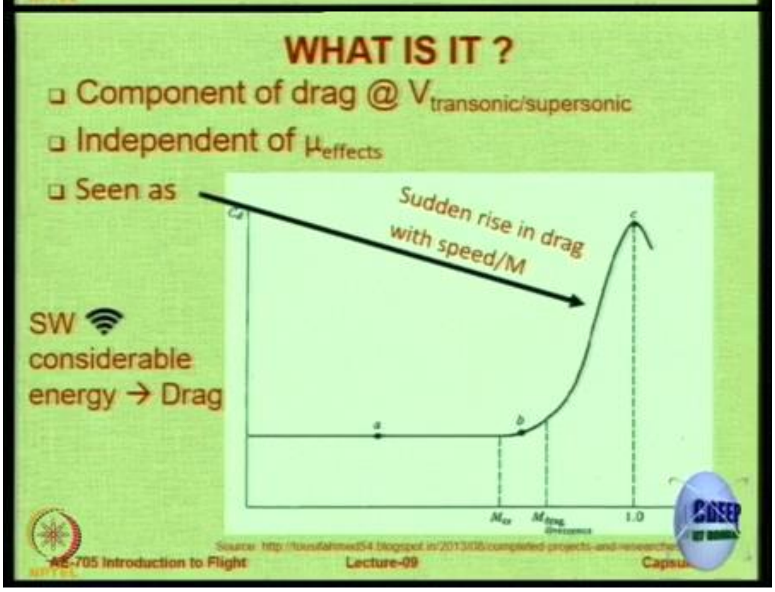

So the problem is that the moment you encounter drag divergence Mach number, the drag is increasing because of shockwave and its effects, so we call this as a wave drag, it is not because of viscosity effects, is not because of fiction, it is because of the presence of this shockwave, so what is it? Let us have a look; it is a component of drag at transonic or supersonic speeds, why do I say transonic speed because the critical mach number normally is, normally why, always it is a mach number below 1 because if the free stream Mach number itself is 1 transonic conditions are going to be there in the leading edge only and that is not a critical mach number because much below that already we had a variation of flow, so it is independent of viscous effects that is the important point okay, so it is seen as a sudden rise in the drag with mach number and the shockwave radiates considerable energy okay and that is what is manifesting itself in terms of drag.

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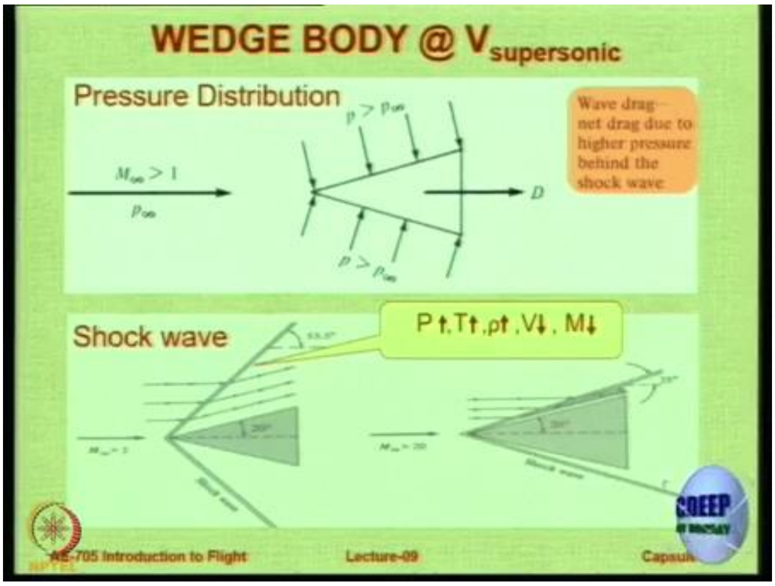

So let see why we have this phenomena, now if you go to supersonic flow and let say we take a wedge body, so on the upper surface we will have P more than P infinity, on the bottom will have P less than P infinity, so the wave drag will be the next drag due to the higher pressure behind the shockwave, a shockwave will manifests itself right from the leading edge in supersonic flow and the angle of the shockwave will be a function of the mach number,

$$\mu = Sin^{-1}\left(\frac{1}{M}\right)$$

So you know, you may not know, but you can assume right now, this is a topic that is covered normally in basic gas dynamics, pressure, temperature and density are going to increase but velocity and mach number are going to decrease, the total pressure and temperature are going to remain constant.

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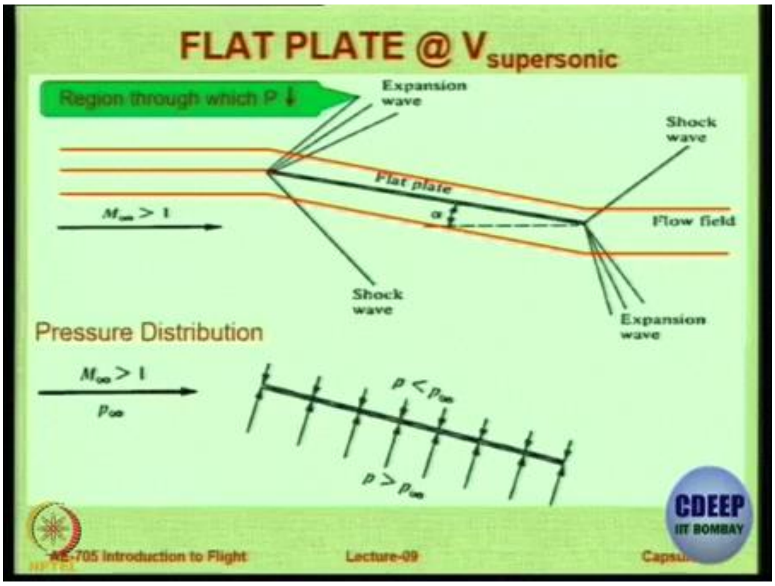

So if you take a flat plate and give it a little bit of angle and submerge that in supersonic flow, M infinity more than 1, so what will happen is that flow comes along these lines, and because it is going to encounter bending downwards, there will be an expansion wave through which the pressure is going to reduce, on the bottom there will be a shockwave okay, there will be a shockwave on the bottom and then at the end again the flow has to straighten, so there is going to be an expansion wave. So an expansion wave can be considered to be as something like an opposite or a corollary of the shockwave okay, so if you see the pressure distribution, the pressure distribution will be such that you will get a net upward pressure and that is what is the generator of lift and this particular net pressure also has got a component on the backside which is the drag okay.

So if you actually minimize the shockwave or the drag because of the shockwave, you should use a very thin leading-edge a very thin profile or you should use a sharp leading-edge because that results in weaker shockwaves and hence lower drags okay.

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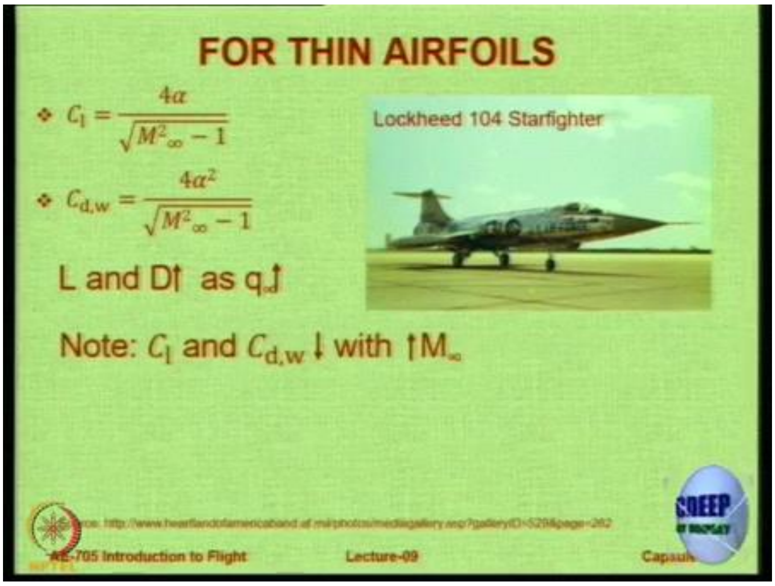

Now let us look at thin aerofoils, for example in this particular aircraft call as the F Lockheed 104 Star Fighter okay, so the value of Cl in supersonic flow can be approximated as

$$C_L = \frac{4\alpha}{\sqrt{M_\infty^2 - 1}}$$

where Alpha is the angle of attack and the wave drag will be

$$C_{d,w} = \frac{4\alpha^2}{\sqrt{M_\infty^2 - 1}}$$

now these two expressions can be derived by you looking at simple gas dynamic equations applicable for supersonic flow, I do not want to do that, I wanted to talk more about some other aspects, so I am not spending time in the class on that, but you can look up yourself.

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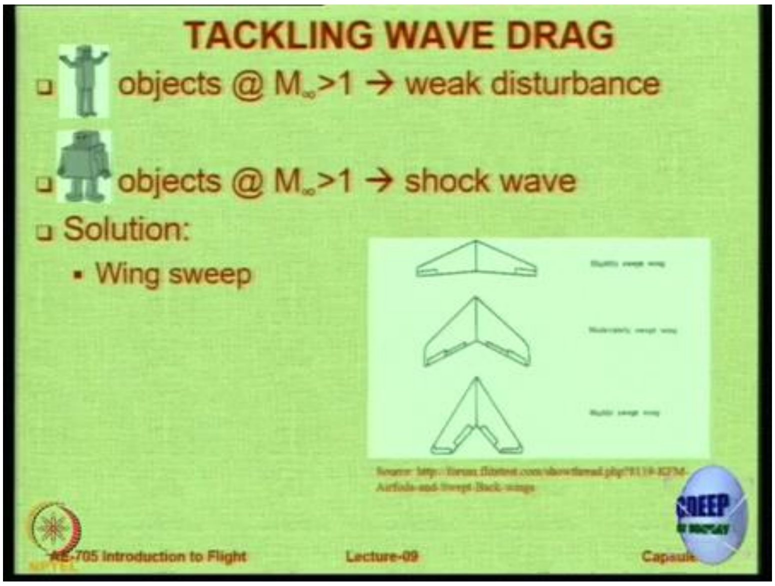

Okay, so let us see how we tackle the wave drag, this is of more importants to us, so if there are thin objects, like a thin aerofoils or a thin wing and if you fly at supersonic conditions because they are thin, they lead to a weaker disturbance and thicker objects like me are going to have higher M infinity, I mean higher effects, thicker shock, stronger shock waves we should fly at supersonic conditions, what is the solution? The solution is that you change the angle at which the air is facing free stream okay.

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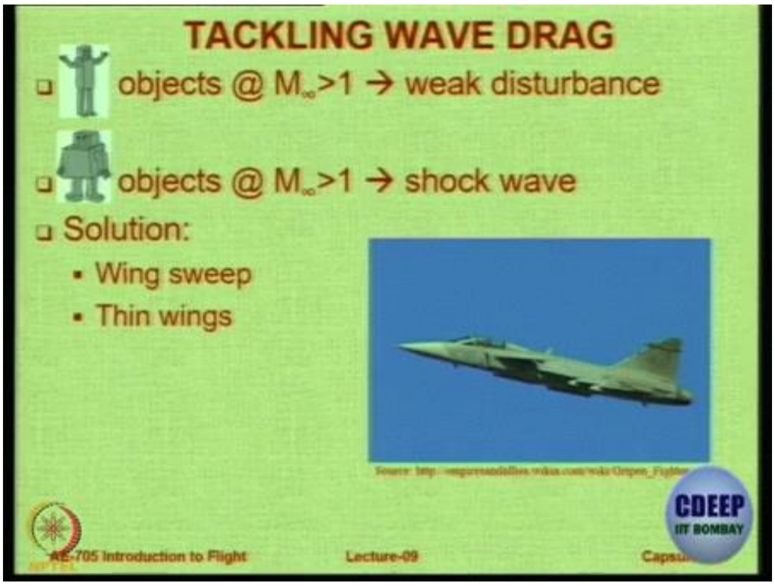

So you have a example of three wings in front of you, so when you provide sweep, will discuss in details about sweep, the other way is that you use thin wings, so the wings which are used on very high-speed aircraft, actually have a very small T by C, T by C ratio would be 4 percent, 5 percent never more than that okay perhaps 8 percent.

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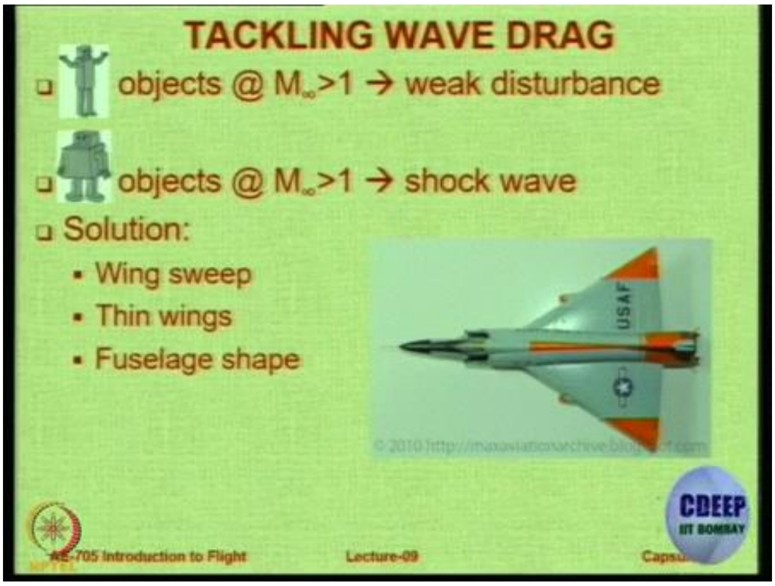

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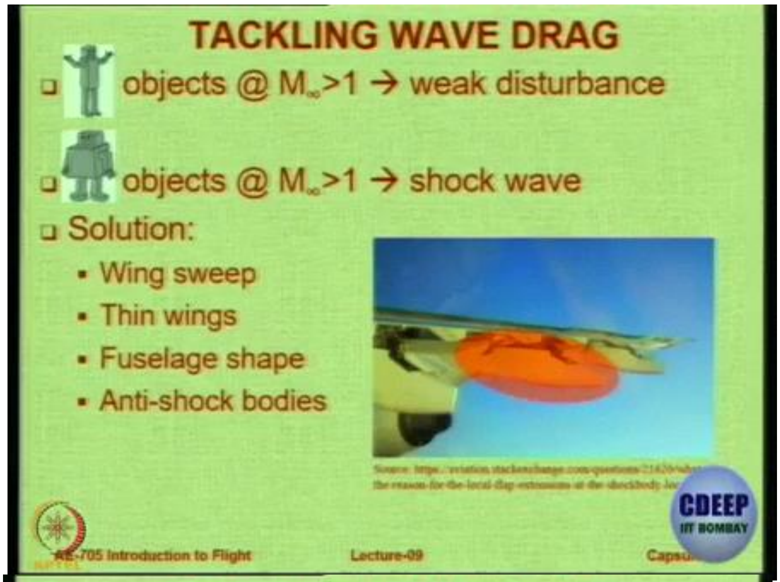

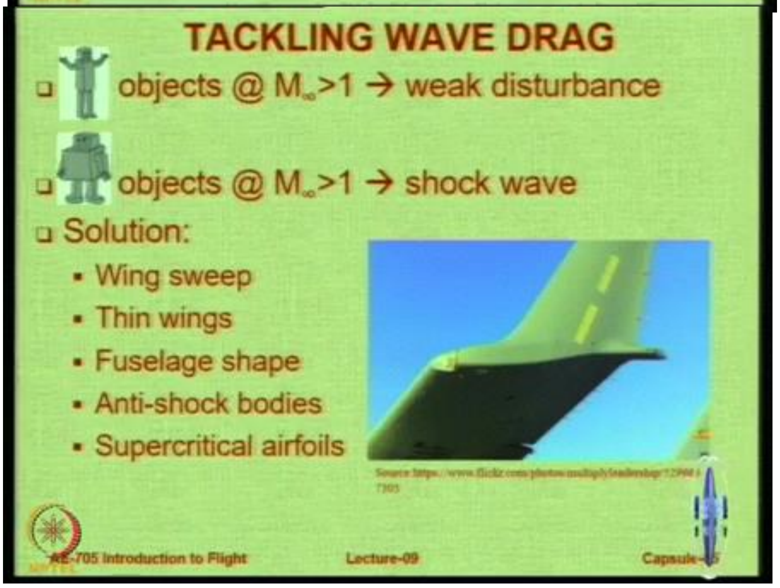

Then you can also go for shaping of the fuselage, which also helps in reducing wave drag as we will see very soon. And finally, you could do proactive reduction in wave drag by putting some bodies or some they are called as Kuchemann carrots or Kuchemann bumps, these are given by an aerodynamicist, who was the chief designer of the Concorde aircraft, the Chief aerodynamicist of Concorde aircraft, he has given these bodies and he has found out that it should present is body and if you shaped them properly then actually you can lead to lower drag in transonic and supersonic flight, so we can also use anti-shock bodies and finally we can use supercritical airfoils, which are designed to reduce the wave drag by giving a geometry, reflex trailing edge okay.

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So these are the solutions, let see one by one, how these solutions are implemented, just a video to show you how one can have a transonic flight even at low altitudes, so why are you able to see this cloud of air over the wing and below the wing, what is the reason? Yes, why are you able to see? Why do not we normally see this kind of thing when you have an aircraft flying and why could you see in this particular flight, yes.

Student: I am Prateek because of the humidity.

Professor: So if you fly in Mumbai city, you will always see cloud overs the aircraft?

Student: Compared to the sea level.

Professor: Yes, so Mumbai is very humid right, we are 70, 80 percent humidity, which means you go to Santacruz airport and stand, every aircraft in Mumbai is going to have a cloud over and above, is it true?

Student Prateek: no.

Professor: So it is not just humidity okay, that is what I wanted to clarify, not humility alone. Okay, anybody else would like to add, yes, please pass on the mic, yes.

Student: Sir my name is Aishwarya and it is due to the fact that the local pressure is quite low, so the condensation of the water vapour, which is present inside the air just condenses and we see it in the form of that cloud.

Professor: Okay, so does this condensation takes place only low altitudes?

Student: Sir it may take place at various places like where humidity is present basically, and more often it likely you to take place at low altitude, while takeoff and landings where humidity is present basically.

Professor: Yeah, so then you come to the same point, Mumbai has always high humidity.

Student: So sir we can also encounter it here also, in fact in our previous lecture we saw a video in which aircraft was landing and there was a cloud on that.

Professor: correct, but my question is if it is only because of humidity and only because of low pressure, then we should always see it when we have an aircraft taking off and landing in Mumbai.

Student: No sir, it should have sufficient velocity, so that the local pressure should be low.

Professor: Correct, so do think this air aircraft is flying at a very special speed that normally planes do not fly, do you think that aircraft at Mumbai do not take off and land at such speeds, so mere presence of humidity is not the reason, there is something else, think about it, think about it. Okay, maybe we can get the answer on Moodle, do you understand my question, I am not saying you are answer is wrong, but I am saying by your argument we should always see it in Mumbai, which has got extremely high humidity, but when I go to the airport, I take soo many flights, very rarely I see it.

So there are certain conditions under which I see okay, the reasoning is not correct, the information is correct, yes it is because of loss of lower pressure, yes it is there because of the condensation of water vapour in the atmosphere, these two are correct, but the reasoning that you are giving that it is because of humidity, then I can encounter and say that we should always see it, so it is fine, it is better that we get the answer on the Moodle okay, oh there lies the answer.

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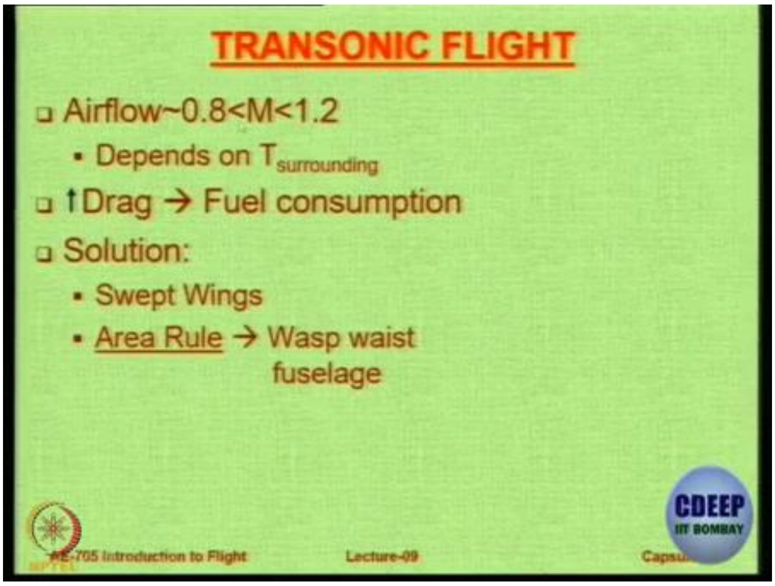

So it depends on also the temperature that is there in the surrounding areas, it should have humility but high temperature, such as we have in Mumbai, in Mumbai what is a condition in Mumbai? ISA +15, right we saw it in the presentation. If you go to a place where there is humidity but temperature is ISA -10 or ISA -15, there is a greater chance of seeing it, so the surrounding temperature also is important for you to get that condensation. Condensation takes place always in low-temperature right, so maybe if you go to Leh airport in winter okay, you might be able to see on a humid day or if it is raining and there is a lot of water vapour in the atmosphere on a very cold place, but then Leh has a problem of high altitude, where density is less so then it becomes a very complicated thing. Okay.

So the issue is that if you have very high drag because of the wave drag, then you have high fuel consumption and the solution is swept wing which you will see. The other solution is area rule or giving a very interesting shape to the fuselage waist, now how this was obtained and what is the science behind it is explained in a nice video, so I thought I just will just show you the video.

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Video: Until Chuck yager and the X1 flew with the sound barrier, on October 14 1947, the sound barrier had finally been broken. The day it was I called blue force approach in the sense that you are rock just rammed the aeroplanes to the speed of sound, but the drive was so high that they used up all of fuel in just about 5 minutes, so was not practical supersonic flight, but it did accomplish, the breaking of the barrier, they needed to be a more efficient way to break the speed of sound.

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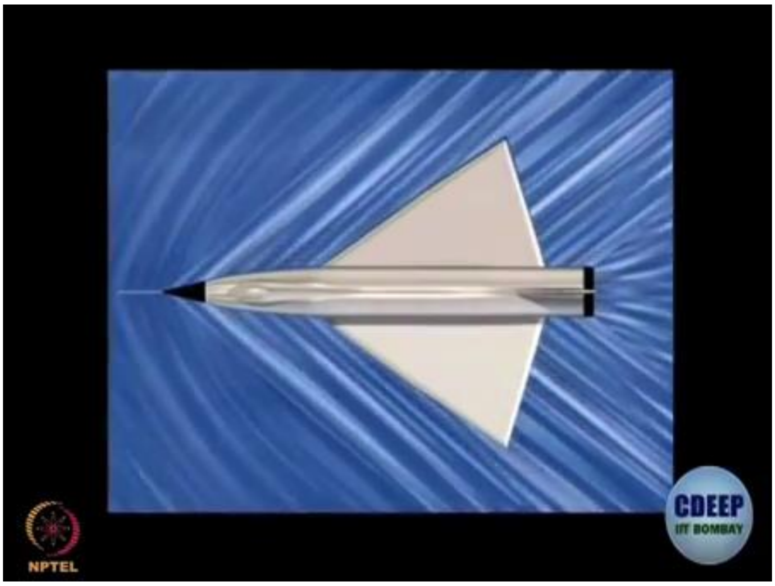

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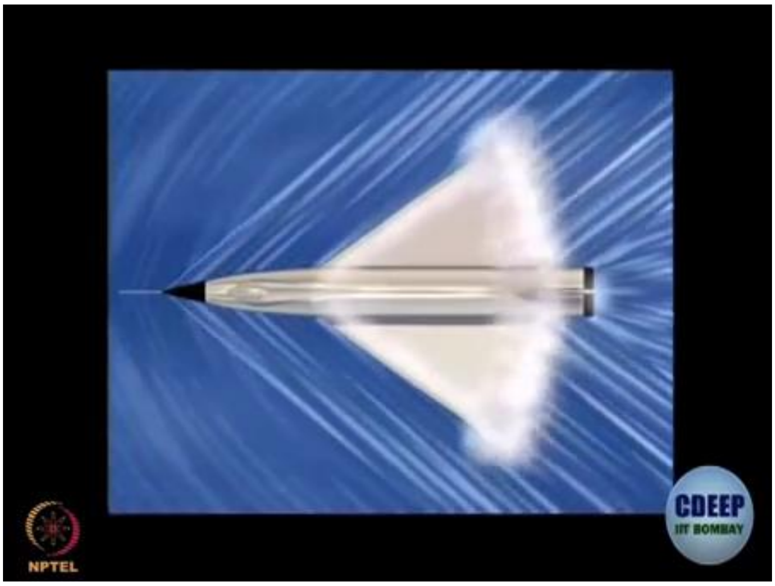

Dr. Richard Whitcomb said out to find a way, Whitcomb found that when a plane reach near supersonic speeds, the drag around the wings would increase by as much as a factor of 5, he saw that much like a bullet, the fuselage was extremely aerodynamic without the wings but when the wings were added in aerodynamic pump was causing incredible amounts of drag that was slowing the plane down, it became obvious to him that he had to find a way to check the pump out of the equation.

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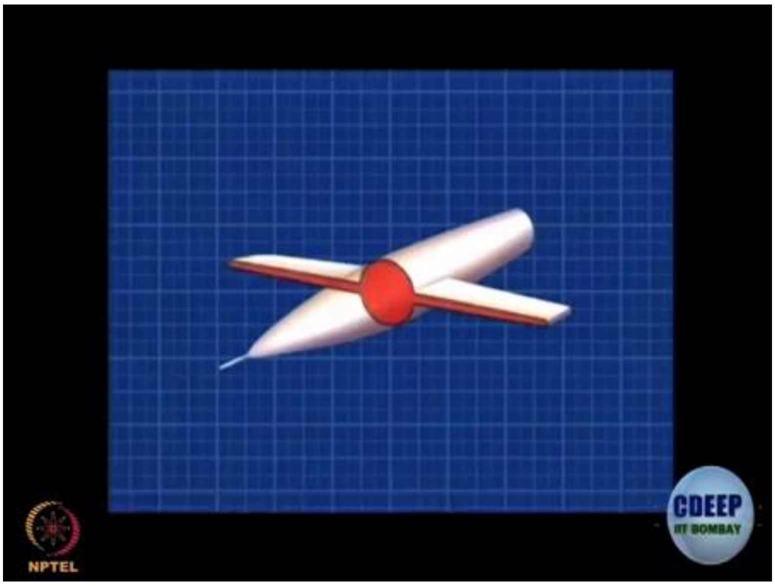

With contests to show that he added the entire area of wings and fuselage together, the drag or aerodynamic pump was exactly the same as the drag of the fuselage with wings. He worked tirelessly to find the solution, when one day as he was thinking about the problem, the solution here in like a bolt of lightning, he must indents or punch in the waist fuselage.

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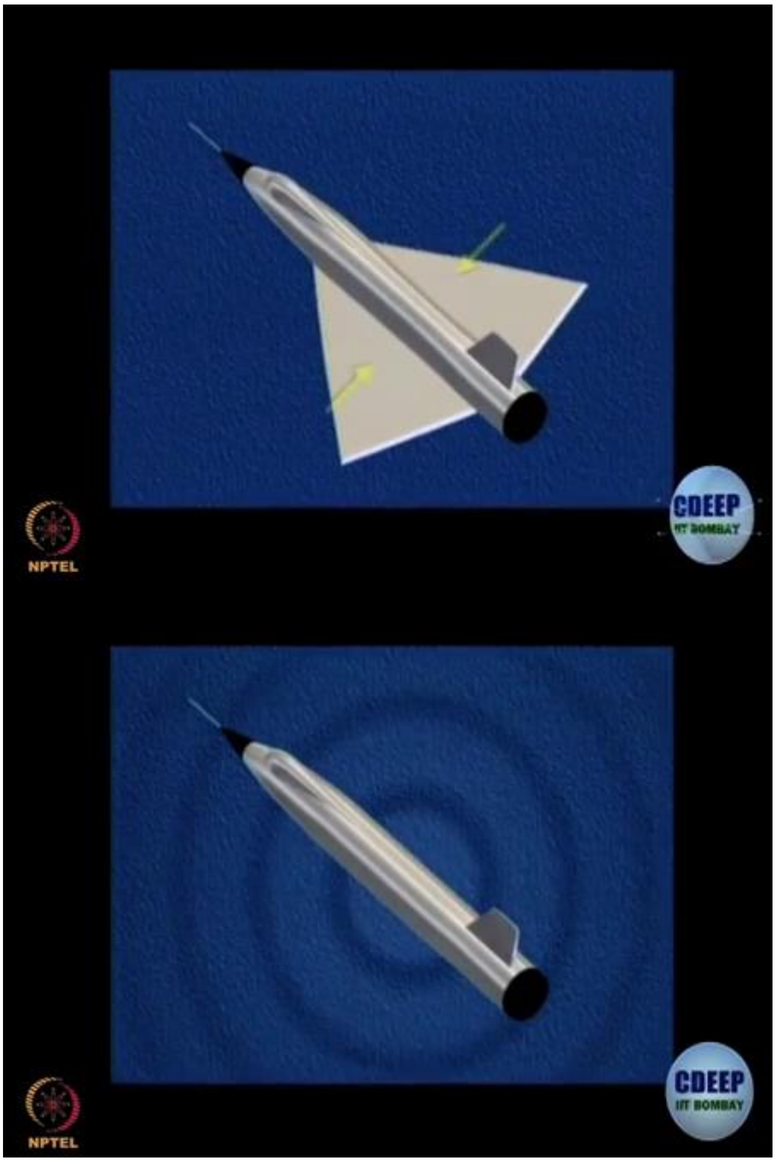

This new shape of the fuselage was closely resemble the shape of cock paddle with composite spanish to find by changing the shape of the fuselage, he took the pump out of the equation and allow the plane to become as aerodynamically smooth as a fuselage without wngs, this very simple fix came to be known as the Area Rule.

I had the idea, then we build model to try and demonstrate it, we built aeroplanes within cock paddle shaped fuselages and blown the whole of the drag as a wing just disappeared.

Professor: So this is Dr Richard Whitcomb from NASA who gave us Whitcomb airfoils as well as the area rule, so what he said just now is that when they were trying to design aircraft to fly faster and faster, they found that as you reach pre-sonic speeds, the fuel consumption increases, so much so that you would consume the entire fuel in only 5 minutes of flight, that means impractical to design an aircraft.

So he found that you should take just fuselage, it is very good aerodynamically in supersonic flight, but the moment you add wings, it creates huge amount of wave drag. So the first experiment, he did was, suppose I distribute the area of the wings over the fuselage and make it like bulged fuselage, he found that the drag of a fuselage with the bulged centre equal to the area of the wing is equal to the drag created by aircraft plus the wing, so that way he figured out that it is something to do with the sudden increase in the area of the cross-section as you come towards, as you go along the length.

So with that, he got this idea one day, not through any scientific reasoning or through any calculations, but just looking at the results and he says what do I do so that I do not get a sudden bulge in the area of cross-section as I go along the length, so that the answer is that you reduce the area of the fuselage or the cross-sectional area of the fuselage.

So he just figured out that the place where you have a wing or a tail, if at that place locally you reduce the area of cross-section of the fuselage, so that the net area of cross-section is not changing rapidly, then you will not get high wave drag and then they verified it by wind tunnel testing and finally we had the area rule and it was applied then to the design of many aircrafts.

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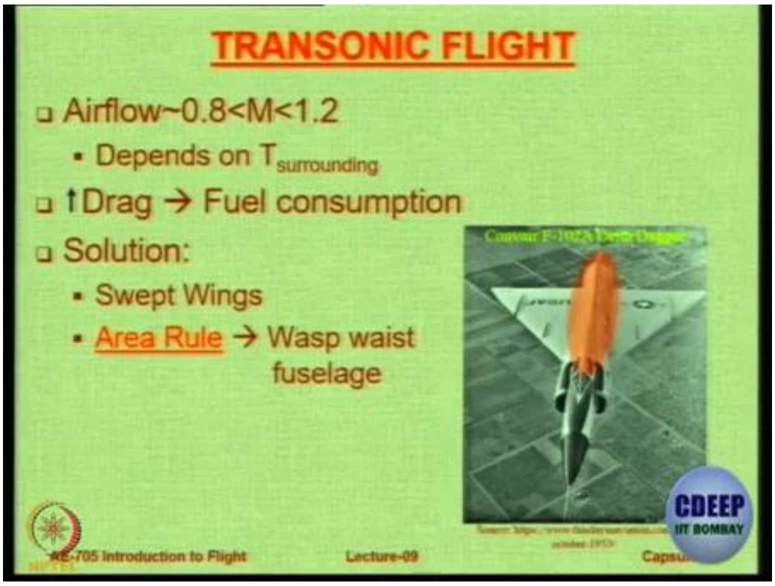

And once that was done it was possible to create realistic aircraft like this, Convair F-102, which could fly comfortably supersonic for a reasonable amount of time, so this one discovery open the way or open the path for high-speed flight in aircraft.

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The other important thing is sweeping the wings, so let us see how sweeping the wings is going to be beneficial. So for the swept back we have to thank Dr Adolf Busemann and Dr Adolf Busemann is a person who first gave the idea that we can encounter or we can, so he was the first one to observe the creation of shockwaves, he was an experimentalist and then he realised that the air over the wing or the drag effects of air over the wing are dominated not by the free stream velocity, but by the velocity perpendicular to the wing, this is an observation, so he just figure out that what is important is not the free stream mach number or the free stream speed, but the speed normal to the wing and if the wing is unswept then those two speeds are equal.

So with this, he got the idea that can we take the wing behind, so that the free stream component or the free stream velocity can have two components, a normal component and a span wise component, so this is called as sweep. A dotted line is unswept or normal aircraft wing and the one on the back is the swept wing and then when needed, you can bring it forward, so along the lateral axis you provide an angle called as a sweep angle and also remember it did not be only back, it may also go forward.

So what we have to provide is an angle between the lateral axis and the wing centreline or a wing reference line, it could be behind sweepback or ahead sweep forward, both of them are aerodynamically identical, that means both of them are going to reduce the wave drag because both of them are going to create a component along the normal to the wingspan, lesser than the free stream component, but the difference is in a sweepback the component along the wing is going to be outwards and in swept forward the component along the wing will be inwards and that makes a big difference.

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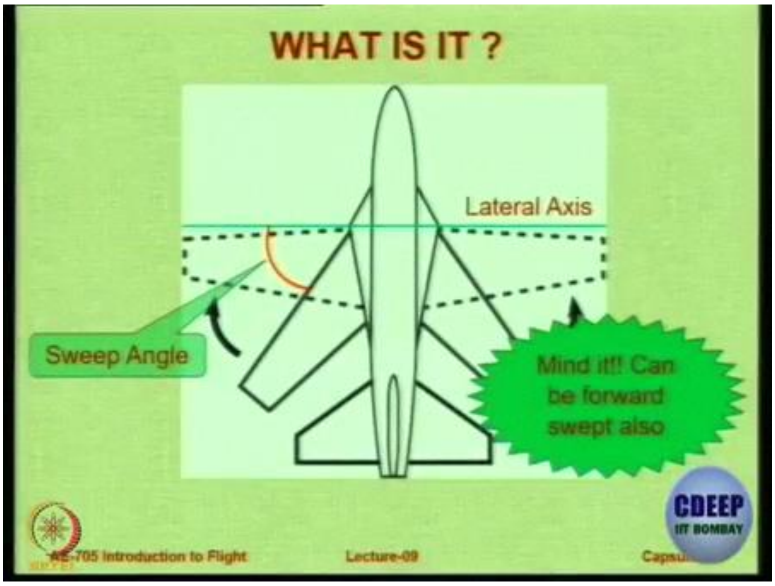

Plus there are other interesting differences also which we will we talk about.