Flight Dynamics II (Stability)

Prof. Nandan Kumar Sinha

Department of Aerospace Engineering

Indian Institute of Technology, Madras

Module No. # 01

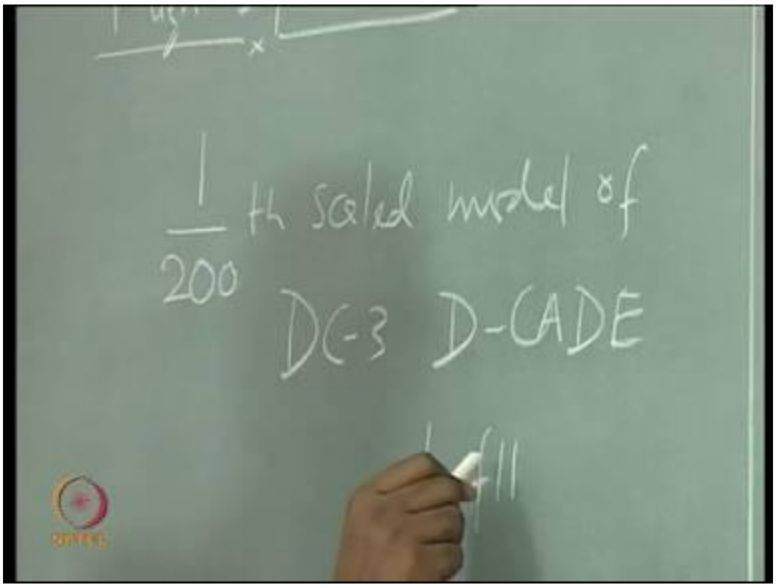
Introduction to the Course

Lecture No. # 02

Basic Aerodynamics

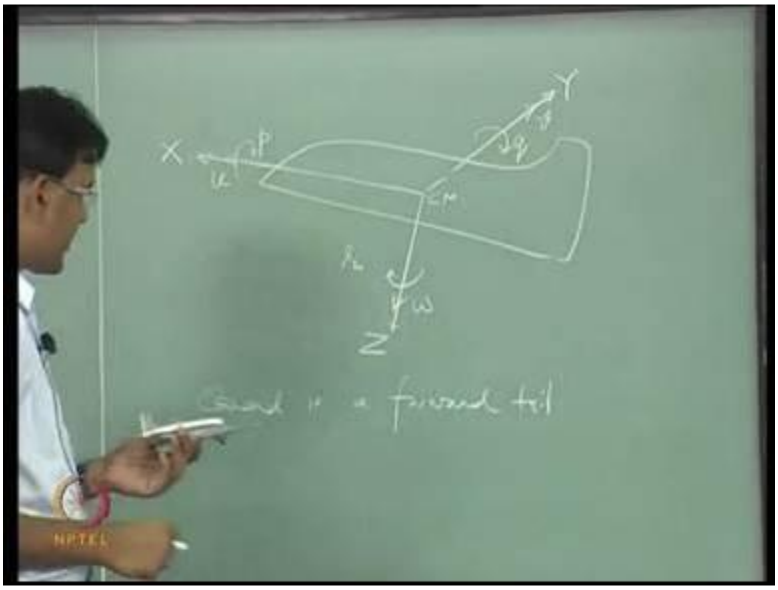
(No audio from 00:11 to 00:23) Lets try to recollect, what we did yesterday through this model. This is 1 over 200 th scaled model of DC-3, name is D-CADE, it is operated by Lufthansa.

(Refer Slide Time: 00:11)



This is just one of the aircraft (models) and let us try to understand the nomenclature that we have discussed yesterday. This part of the aircraft, which is used to carry the passengers and the freight is called fuselage. Wings are these two surfaces. This is a twin engine propeller aircraft.

(Refer Slide Time: 01:00)



You see two engines symmetrically located with respect to a plane that we will discuss about. This surface is called vertical tail and this surface is the horizontal tail (Refer Slide Time: 01:20). Remember yesterday we defined an axis system fixed to the aircraft X, Y and Z, fixed at the origin at the center of gravity (CG) or the center of mass of the aircraft (No audio from 02:09 to 02:24).

This X axis can be taken as the line joining the center of the fuselage cross sections. If you take the fuselage cross section, there will be a center for that, and when you join (all) the center(s) of the fuselage (all X-sections) along this (its) length, you can define this X axis as that line. Or, if the CG of the aircraft is not lying along that line, then we have to define this X axis differently. This X axis has to (must) pass through the center of gravity or the center of mass of the aircraft.

The aircraft is actually symmetric about this plane, which is passing through the axis X of the aircraft (Refer Slide Time: 03:46). If you look at this aircraft model carefully, this is the (XZ) plane which is dividing the aircraft into two equal parts and that plane is the plane of symmetry, also called longitudinal plane of the aircraft.

In that (longitudinal) plane, this (the) Z axis is defined as perpendicular to the X axis. Y axis completes the orthogonal coordinate system; Y axis is perpendicular to (both) X and Z axes. The motion of aircraft along the X axis in the forward direction was associated with the variable u that was the velocity of aircraft along (the) X axis.

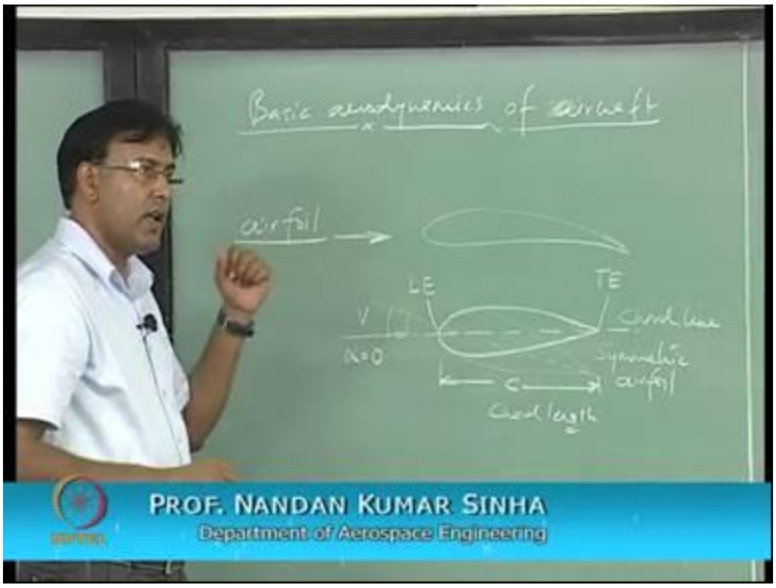
The side velocity is along the Y axis, which is along the span of the wing and if you look at this system, the right handed system tell us that if this is the X axis, the Y axis is away from me along this part of the wing and the Z axis is downward. So, side velocity v is along the Y axis of the aircraft, it is like this, and, the downward velocity w is along the Z axis, which is perpendicular to the X and the Y planes, like this. This gives you 3 translational degrees of freedom of the aircraft.

Talking about 3 rotational degrees of freedom, the roll motion of aircraft is defined along (about) the X axis and it is like this (Refer Slide Time: 06:33). So, this is the roll motion and the associated variable with this roll motion is roll rate, which we talked about yesterday. This roll, a positive roll is; right to me this (starboard side) wing going down and the left (port side) wing going up. The pitching motion is about the Y axis, which is this axis, and it is (the motion is) in the XZ plane. So, aircraft pitching up means, a positive pitching motion, and that is going (looking) like this (Z axis moving towards X axis) (Refer Slide Time: 07:24). Aircraft is rotating about CG in this fashion (Z axis moving towards X axis) if we have positive pitching and the associated variable is the pitch rate q. A negative pitching motion is in the other direction. The other motion is the (a pure) rotational motion about the Z axis of aircraft and this motion is called yaw. The wing to the left to me (port side wing) is going forward and this wing to my right (starboard side wing) is coming towards me (X axis moving towards Y axis), this is a positive yaw motion and the associated variable to that (yaw motion) is (yaw rate) r.

Should you really wonder why these surfaces are located on the aircraft in this fashion? For example, if you look at this wing, this wing is lying low on the fuselage. The engines are lying in front of the tail and on the wing, we could also have location of engine/s somewhere else, we could also have (only) one engine, for example. Here we see two engines. If we look at the vertical tail, it is looking up, vertically up, why it is not upside down, that is also one might wonder about. And the horizontal tails. Tails are called tails because they are lying behind the wing, but there are surfaces which are also like tails, but they lie in front of the wing and those are called forward tails. If you remember, canard is a control surface which can be called a forward tail.

What I was explaining is; you would wonder why these surfaces on the aircraft are located in the way they are located. This wing could have been actually straight, not tapered like this here, it could be lying on top of the fuselage, it could be lying midway and look at the location of the horizontal tail. Horizontal tail is lying above the wing. What are the reasons for all these things, to come to such a design, that is what is the subject of study of flight dynamics course. After explaining all that, let us look at how wing is actually (contributing to the motions of aircraft), so let us try to understand some of the basics (of) aerodynamics.

(Refer Slide Time: 11:13)



Basic aerodynamics of aircraft. An aircraft is actually consisting of lot of aerodynamic surfaces, of which, you can see this wing, you can see the tail, tail is also (an) aerodynamic surface, vertical tail and the horizontal tail. Let us look at the section of this wing, take the section of this wing, the way it looks like is this (refer to sketch above). This shape is called airfoil, airfoils will constitute the wing.

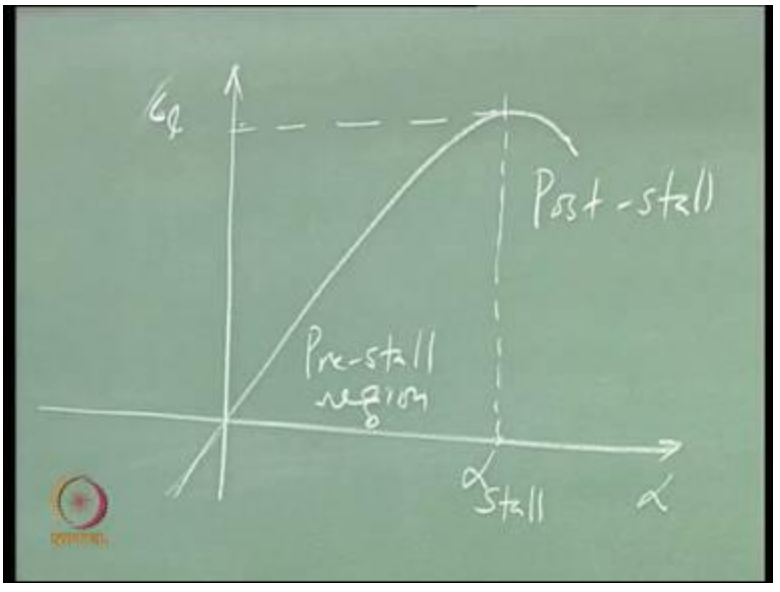
Any section along the Y axis of the aircraft (parallel) to the XZ plane on the wing will give you this section (airfoil). And this is what actually is resulting in giving you lift in flight, when air is flowing over this surface. Let us try to understand some of the basic features of this airfoil which will help us defining some parameters later on.

Let us define an airfoil shape first. Much of this can be covered in the aerodynamics course and I assume here that you have (already) seen (much of) what I am going to talk about (Refer Slide Time: 13:30).

This airfoil which looks symmetric about this line is called a *symmetric airfoil*. This part above this line is a mirror image of the part which is lying below this line, and this line is called the *chord line*. This length joining the leading edge of the airfoil and the trailing edge is given by this distance, which is the *chord length* of this airfoil. So, this airfoil is symmetric and what it means is, if the relative wind is coming along the chord line of this airfoil, then the angle of attack which is measured with respect to this chord line is 0 (Refer Slide Time: 14:20).

When you change the orientation of this airfoil, so you can rotate this airfoil and if this is the direction of velocity then, the angle of attack will change. For example, if this is rotated, the whole airfoil is rotated like this, then the angle of attack is this. The chord line for this airfoil, (when) it is rotated like this (clockwise), this (chord) line which is making an angle with the velocity vector is giving you the angle of attack which is positive. This (positive angle of attack) gives you a lift over the airfoil which is symmetric in this case.

(Refer Slide Time: 16:40)



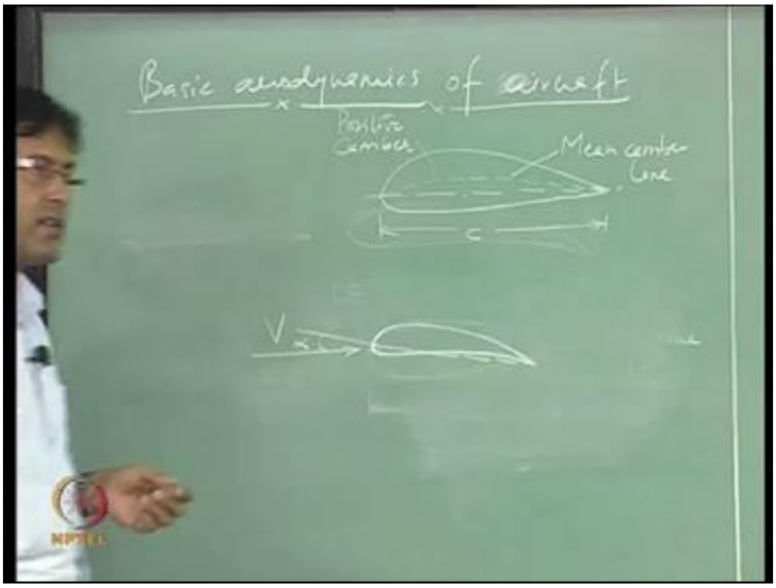
The profile of the lift curve of this (symmetric airfoil) section, which is denoted by this small c_l against angle of attack, looks something like this (refer the sketch), passing through this 0, origin of the c_l versus alpha axes. It is not possible that you keep changing (increasing) this angle of attack (forever and) keep getting (continuous) increase in lift.

At some point (angle of attack), what happens is, flow over the airfoil starts separating toward the leading edge at some point because of which there is a loss in lift.

Instead of creating lift (with increase in angle of attack), the lift actually starts falling down and that is because of the pressure distribution over the top and the bottom surfaces (reversing). There is a range of alpha within which you can keep getting increase in lift because of the relative wind coming onto the airfoil.

Beyond this alpha which is called alpha stall, flow separates over this airfoil and there is a drop in lift. This region where you see almost linear variation of c_l with respect to alpha is called, pre-stall region, and beyond this alpha stall you have post-stall region (Refer Slide Time: 18:30). So, in order to derive maximum efficiency from our wing in terms of producing lift, what we would want to do, in normal flights, is to fly in this pre-stall region, where we can keep changing angle of attack and keep getting (proportional) increase in lift.

(Refer Slide Time: 19:36)

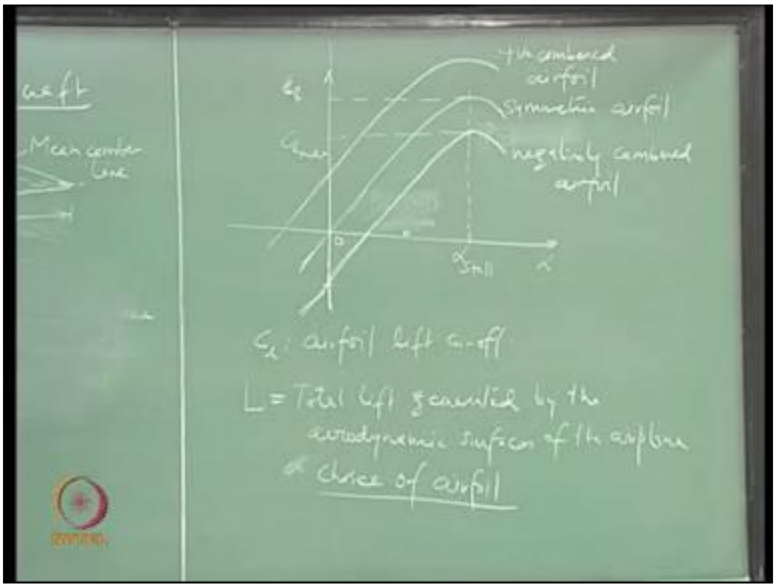


This is for this symmetric airfoil. Now let us look at another airfoil which is not symmetric. This is one such airfoil which is not symmetric and the major advantage of using such airfoil is to produce lift even at zero angle of attack (Refer Slide Time: 19:40). So, let us see what happens here. We have this airfoil which is bulging on the top side and it is flattened on the bottom side. This is the chord length, which is joining the leading edge and the trailing edge of the airfoil. We can define another curve which is joining the center of each section of this airfoil, this line is called *mean camber line*. In this case, in the symmetric airfoil case, the mean camber line is same as the *chord line*.

Here the mean camber line is slightly away from the chord line, and if this is the case, when the mean camber line is lying above the chord line, we say that it is a positive camber. Lets look at what happens in this case, when we have, lets say, velocity vector aligned along this (horizontal) line. Now because of the chord (chord line rotating up in case of positively cambered airfoil), a similar case if you want to represent here, then what you need to do is, you need to define this line (tangent to mean camber line at the leading edge; in the top figure) parallel to the velocity, relative wind, vector.

If you want to draw parallel between the two airfoils, then let us say this (horizontal vector) is the velocity vector of the relative wind and the airfoil is positively cambered airfoil now. What is happening in this case; this is one such airfoil. The chord line is joining the leading and the trailing edge. What you are seeing here is, by giving a camber to a symmetric airfoil you get an increase in angle of attack. For the same velocity of relative wind, but for a different camber of the airfoil, you see there is an angle of attack associated with it. And what it results in is, giving you a positive lift at zero angle of attack.

(Refer Slide Time: 24:01)

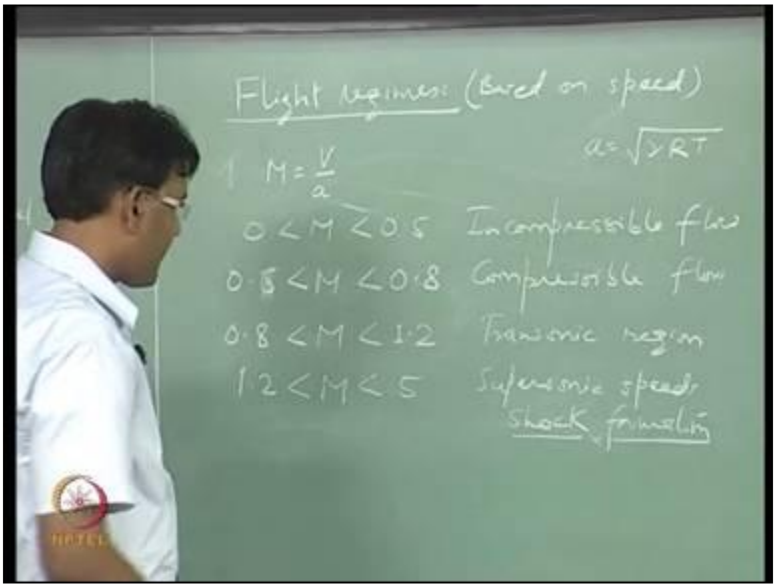


In a similar fashion, we can invert this airfoil (upside down) and then the airfoil becomes a negatively cambered airfoil. In that case alpha becomes negative. So, at zero angle of attack what you get is a negative lift in the case of negatively cambered (No audio from 25:09 to 25:40) airfoil. Clearly if we want to fly aircraft at alpha which is as low as 0 degree, then we would prefer the positively cambered airfoil over the other two cases because it gives me the higher lift coefficient. c_l is here *airfoil lift coefficient*.

You can see clearly an increase in the maximum c_l that you can get in the three cases. Maximum c_l is at alpha stall. Where all these things are coming into picture, let us look at that. Lift is, lift over the wing; the total lift generated by the aerodynamic surfaces of the airplane is going to be depending upon the airfoil that you choose. In case you have chosen this positively cambered airfoil for the wing, that is going to give you much higher lift as compare to the other two airfoils. So, this is clearly depending upon the choice of airfoil.

Choice of airfoil is also depending upon the (speed) regimes of flight that you want to fly. Let us look at some of the flight regimes based on speeds.

(Refer Slide Time: 28:07)



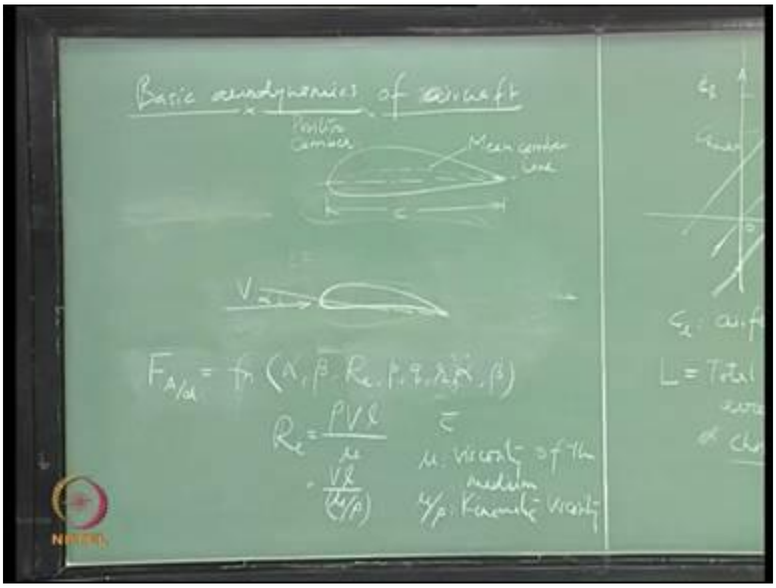
(In order to define speed regimes) We talk about Mach number which is the ratio of the speed of the airflow (relative wind velocity) over the speed of sound. The speed of sound is a function of the temperature. If you talk about this, (Mach number) 0 to 0.5, now if you want to operate your aircraft only in this flight regime, then the choice of airfoil should be different because the flow in that case is incompressible.

Regime of flight between 0.5 Mach number and 0.8 is compressible. So, flow over airfoil in this case is compressible in this speed regime. Mach number above 0.8 and below 1.2 is transonic region, where the wing can encounter some of the discontinuities in the airflow because of presence of shock; weak or strong depending upon the speed, with whether it is close to 0.8 or close to 1.2. There is lot of discontinuities in the flow taking place in this region of speed.

There is this supersonic regime of speed, Mach number here is greater than 1.2 and less than 5, clearly here there are phenomena associated with shock formation taking place. In front of the wing or any other surface which is looking like a wing, there will be a shock formed, then because of the shock formed in front of the wing, there will be discontinuities in the flow.

Depending upon what regime of speed we intend to fly for a longer duration, so if you look at the typical flight profile, you have to start with low speed to take off and then attain the height at which you want to fly your aircraft, and then increase the speed to the speed regime in which you want to fly your aircraft. And the third place is landing, if you do not want to talk about of some low speed maneuvers for example, level turn and so on. So, these are the flight regimes that one can design the aircraft to fly in, depending upon the requirements, and the choice of airfoil or the wing section is going to be dependent upon the speed regimes.

(Refer Slide Time: 32:57)

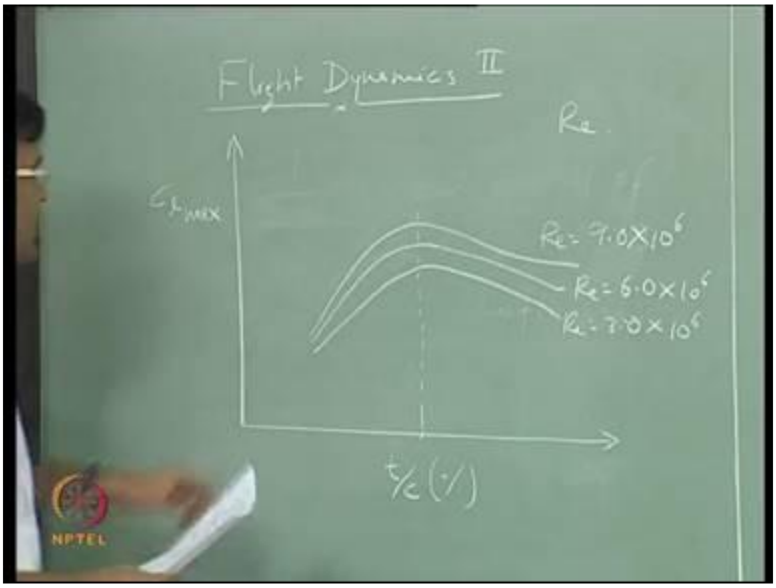


Thats why we said in the first class that, the forces, the aerodynamic forces are, I want to just write F for all aerodynamic forces, it is going to be a function of angle of attack, side slip angle, and the Mach number. If we want to include also the compressibility factor with the Mach number, then you are talking about what is called Reynolds number. Reynolds number is defined as the density into the speed into l, which is a characteristic length. In the case of airfoil, this l could be taken as the mean aerodynamic chord and the viscosity of the fluid.

You can also write this (Reynolds number) as: mu is the viscosity of the medium and mu over rho is the kinematic viscosity. So, in general these forces are also going to be functions of the rates and the rate of change of these angles and similarly, moments are also going to be functions of these variables. If we want to look at how Reynolds number is having an effect on the c_l, this lift coefficient of the airfoil with respect to also the thickness of the airfoil, we can quickly have a look at that (Refer Slide Time: 35:39)

(No audio from 35:29 to 35:44).

(Refer Slide Time: 35:39)

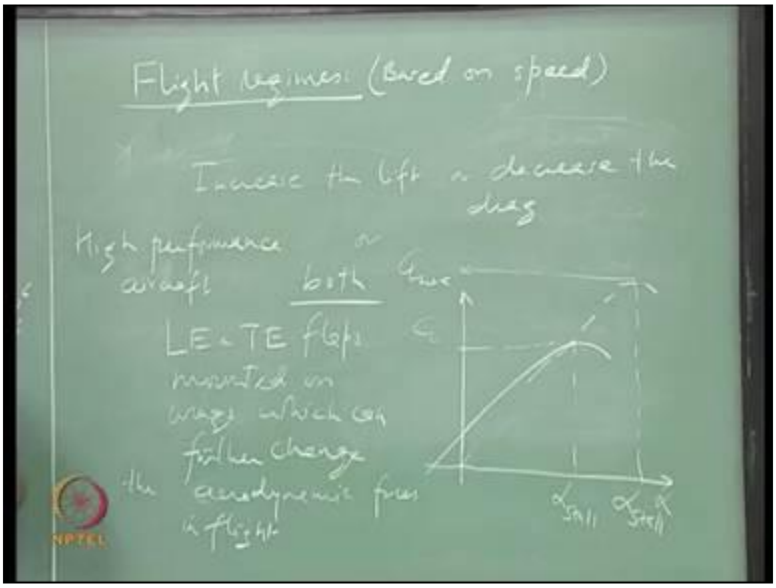


On the x-axis we have, we want to look at how $c_{l\max}$ is varying with Reynolds number and the thickness to chord ratio, which is in percentage. Thickness of the airfoil is actually the maximum thickness. So wherever you find the maximum distance between the top surface and the bottom surface, that can be taken as the maximum thickness of the airfoil.

If we plot all the thickness, thickness or the maximum thickness are the same. So, let us try to plot the $c_{l\max}$ versus the thickness of the airfoil in terms of the percentage of the chord and the effect of the Reynolds number on the $c_{l\max}$. Clearly if you increase the speed of flow over the airfoil, then you will get more lift and this one is for the highest Reynolds number, which is, 9×10^6. And it falls down, $c_{l\max}$ falls down with respect to this Reynolds number.

If we decrease the Reynolds number by one third and c_l, decrease in the $c_{l\max}$, at different values of this t by c ratio in terms of percentage, you see a fall in $c_{l\max}$ with respect to the speed that you are flying at. So, clearly there is a t which is giving us the $c_{l\max}$ in different speeds of flow over the airfoil. We have chosen some airfoils depending upon our need and we are getting lift. Major contribution coming to the lift is from the wing. Let us say we have decided on an airfoil for the wing. Now, after deciding that, the wing is formed and now what we want do is, we want to change this lift. So, there will be a lift corresponding to each angle of attack because of the airfoil that we have chosen. Now, what we want to do is, we want to increase the lift in flight, when you are changing the flight speed regimes or the angle of attack, what you want to do is, you want to increase the lift or decrease the drag or both.

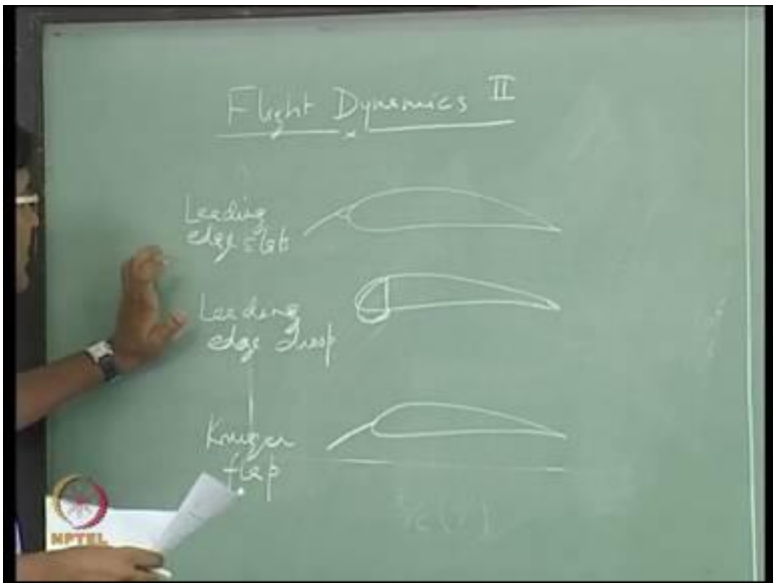
(Refer Slide Time: 40:01)



In case you want to change the lift drag profile or both together, of course both of them are going to change together because of the flow field changing over the wing; due to the change that we are looking at now. There are leading edge or trailing edge flaps mounted on wings, which can further change the aerodynamic forces in flight.

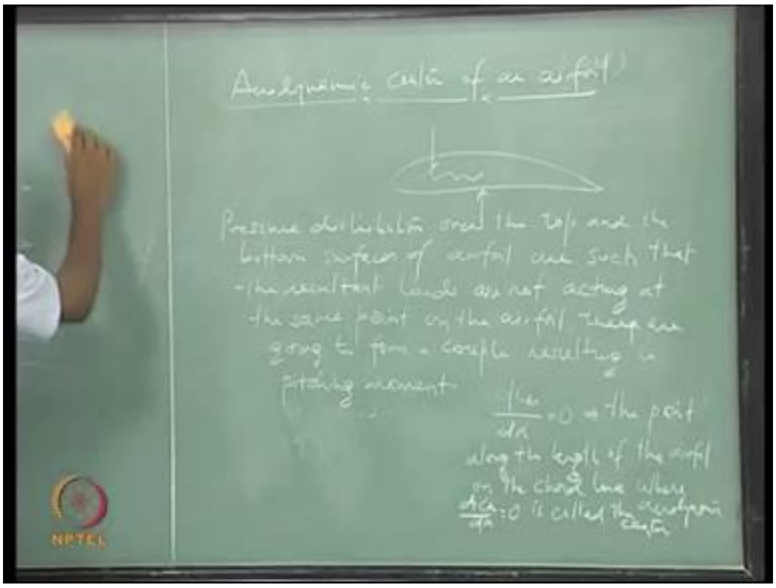
So, if the c_l versus alpha curve is looking like this, you know it can be, so this for symmetric airfoil. We can go back and assume that, the wing is made of positively cambered airfoil, and lets say we get this kind of c_l versus alpha profile. In flight, this profile can be changed using the trailing edge and the leading edge flaps, which are normally mounted on high performance aircraft to not only change the maximum lift coefficient, which is now this, previously it was here, but also to change the alpha stall (Refer Slide Time: 42:30). So, use of trailing edge and leading edge flaps are now very common on higher performance aircraft.

(Refer Slide Time: 43:05)



Some of the examples of these flaps are: so this kind of arrangement is called; there is a thin curved surface, which is lying in front of the leading edge of the wing, is called *leading edge slat*. There is another thing wherein, the leading edge of the airfoil can be given a droop in flight, so this is called, this kind of arrangement is called leading edge droop, this is called Krueger flap (Refer Slide Time: 44:11). These devices are used on higher performance aircraft nowadays to change the lift profile in flight.

(Refer Slide Time: 44:56)



Let us also define what is known as aerodynamic center of an airfoil. If you look at pressure distribution over the top and the bottom surfaces of airfoil, that is what is giving us the lift, resulting pressure distribution, the resulting load due to the pressure is what is giving us the lift. And if this load is coming because of the pressure on the top surface and the bottom surface, (if) they are not lying on the same point, then they are going to give rise to a moment.

So, if the pressure distribution over the top surface and the bottom surface of airfoil are such that, the resultant loads, loads from the top and the bottom surfaces, are not acting at the same point on the airfoil, they are going to form a couple resulting in a pitching moment. So, let us say, the resultant loads are acting at two different points, then this kind of arrangement of resultant of loads are going to give rise to a pitching moment.

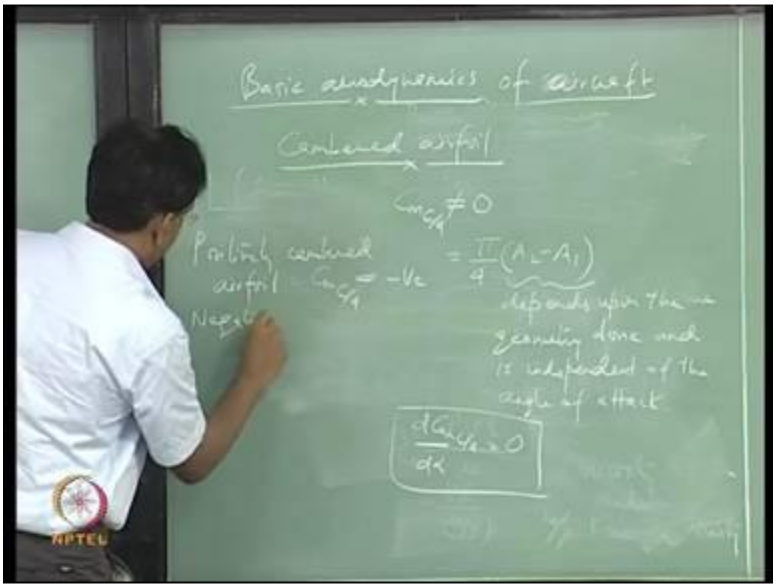
There is one point on the airfoil along the chord of the airfoil, where the change in pitching moment with respect to change in angle of attack is 0, and that point on the airfoil is called the aerodynamic center of the airfoil. So, the point along the length, a point along the length of the airfoil on the chord line, where $dC_m / d\alpha$ is 0 is called the aerodynamic center. Usually for a symmetric airfoil, the aerodynamic center is at the quarter chord length of the airfoil (from the leading edge facing the flow).

(Refer Slide Time: 49:56)

For a symmetric airfoil, the aerodynamic center is lying at the quarter chord length from the leading edge. For symmetric airfoil, the aerodynamic center is also the point, where the resultant load on the top and the bottom surfaces are acting, and that gives me $C_{mc/4}$, if that is the case, we can also say that $C_{mc/4}$ for the symmetric airfoil is 0.

What it means, in the case of symmetric airfoil, the loads, the aerodynamic loads, are acting at the quarter chord length, so there is no moment created because of the loads, so $C_{mc/4} = 0$ and $dC_{mc/4} / d\alpha$ is also 0.

(Refer Slide Time: 52:23)



In case of cambered airfoils, the loads coming from the aerodynamics are not acting at the same point and they are giving rise to a moment about the quarter chord which is not 0. $C_{mc/4} \neq 0$, you get a pitching moment. And this is actually equal to pi over 4 into some parameter $(A_2 - A_1)$ which is not depending upon, so this parameter depends upon the geometry of the airfoil alone and is independent of the angle of attack.

This being a constant, and independent of angle of attack, $dC_{mc/4}/d\alpha$ for any airfoil, which is a cambered airfoil is 0. What it means is, the quarter chord of the airfoil in all three cases can be taken as the aerodynamic center of an airfoil and this will have some implications which we will see later on. $C_{mc/4}$ for the cambered airfoil is not equal to 0; for positively cambered airfoil, this $C_{mc/4}$ is actually a negative number, and for negatively cambered airfoil, this $C_{mc/4}$ is a positive number.