Basics of Mechanical Engineering-3

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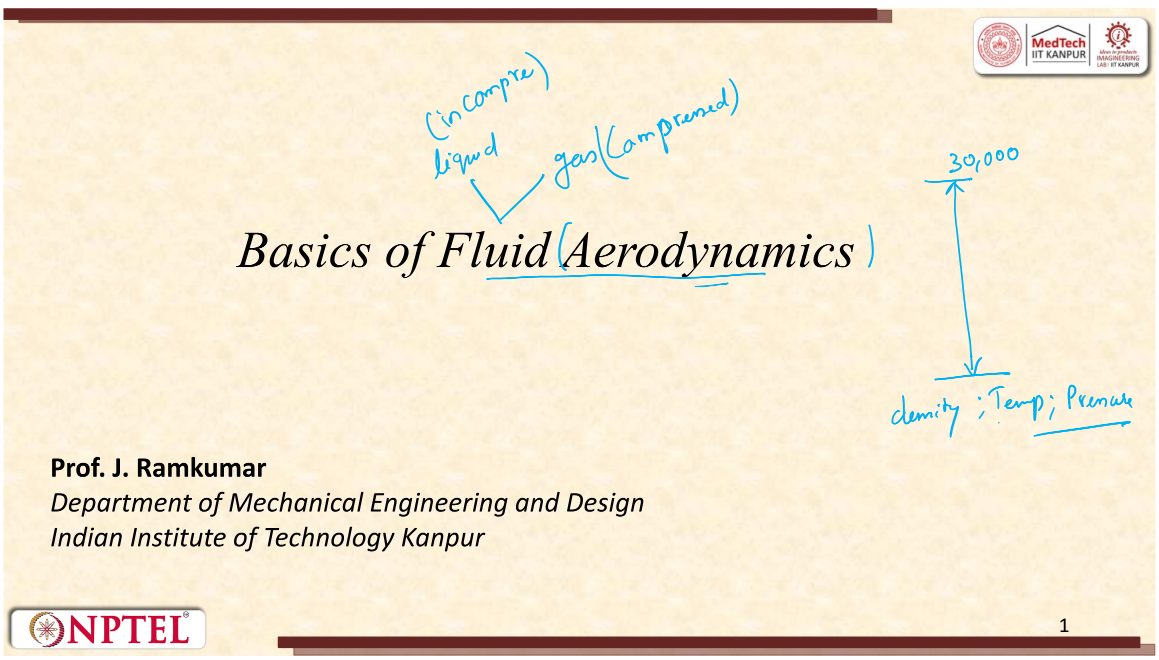
Week 09

Lecture 40: Basic of Fluid Aerodynamics



Welcome to the new lecture on Fluid in the Area of Aerodynamics or in the Area of Aerospace. Aerodynamics clearly says dynamic means it is a changing phenomenon with respect to time. Aero means it is like an aeroplane and other things. So, it is going to talk about what is happening above the land surface. It is a very interesting phenomenon because when you try to see the Earth's atmosphere, the flight generally travels at around 30,000 feet.

Normally, they will go in that field because here they will not have much turbulence. So they will always go 30, 33, 35,000. That's how they go, so that they can travel very fast with minimum resistance. So now the question which comes to your mind is, what happens to the temperature? What happens to the pressure? Now, how will the thermodynamic properties change?

Now, when these two change, what happens to the density of the air? So all these things come into your thought process. Now in this lecture and in the next lecture, we will try to understand a little bit more about the aerodynamics of fluids. And friends, when we talk about fluids, we clearly saw that liquid is one part and gas is the other part. So these become compressed fluids and incompressible fluids. So, by and large, they are both linked. So, we will try to put effort in this lecture to understand more about the aerodynamic properties.

Contents

- Aerodynamics
- Fundamental Laws of Aerodynamics
- Lift
- Drag
- Airfoil: Definition, Application
- Anatomy of an Airfoil
- References

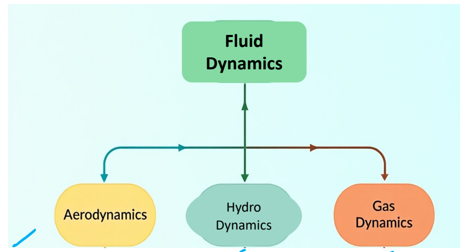
So, the content of this lecture goes like this. First, aerodynamics. We will try to see what aerodynamics is. Then, what are the fundamental laws of aerodynamics? This will be good for you to understand because we studied some laws in fluids. And now, let us see how things change or how they get modified a little to meet the requirements where the fluid is compressible. Then, we will try to understand lift and drag because this is very important when talking about planes and aerodynamic profiles. Then, the anatomy of an aerodynamic profile, and finally, we will try to see the references.

Introduction

It does not make sense to classify the study of the dynamics of both liquids and gases under the same general heading, called fluid dynamics.
Certain differences exist between the flow of liquids and the flow of gases.

Therefore, fluid dynamics is subdivided into three areas as follows:

- **Hydrodynamics**—flow of liquids
- **Gas dynamics**—flow of gases
- **Aerodynamics**—flow of air



It does not make any sense to classify the study of the dynamics of both liquids and gases under the same heading called fluid dynamics because it is a completely different ball game: compressible fluid, incompressible fluid. So, we cannot put them in one topic. So, let us clearly distinguish three. So, one is called aerodynamics. The second is called hydrodynamics. And the third one is called gas dynamics. Hydrodynamics is very important for people in civil engineering and mechanical engineering.

Aerodynamics is very important for people in the field of aerospace. And gas dynamics is also in the same category. So, certain differences exist between the flow of fluid and the flow of gas. So, that is why we divide them into three categories. Therefore, fluid dynamics is divided into three areas: hydrodynamics, flow of fluid—this can be water or any other fluid. In the processing industry, particularly the pharma industry, we use multiple fluids apart from water. But water is the most commonly used. That is why in all the cycles we study, we always examine the phenomena of steam. Then comes the flow of gas. The last one is the flow of air. So, these two are to some extent linked. This is gas of one particular domain. Air is the normal one, which is a mixture of several gases.

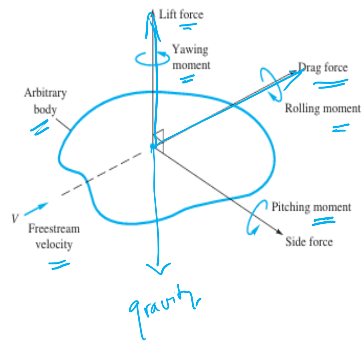
Aerodynamics

Aerodynamics is a field within fluid mechanics that focuses on the forces and moments experienced by bodies immersed in a fluid stream.

When a body is placed in a fluid stream, it experiences forces and moments.

The primary forces are:

- **Drag**: The force on the body parallel to the free stream and positive downstream. It is essentially a flow loss that must be overcome for the body to move against the stream.
- **Lift**: A force perpendicular to the drag, often performing a useful task like supporting the body's weight.



Aerodynamics is a field within fluid mechanics that focuses on forces and moments. Friends, we have seen three things in the past. One is the conservation of mass, conservation of energy, and conservation of momentum. These are the three basic laws. We will have to solve any problem using any of these three, all three, or maybe two, depending upon your specific requirement. That is what we saw in the laws of fluid mechanics. So, aerodynamics is a field within fluid mechanics.

It focuses on forces and moments experienced by a body immersed in a fluid stream. So, friends, what happens when we place a body inside water? The same phenomenon occurs. For example, submarines. The same principle applies.

So, when we talk about ships, the phenomena we study in aerodynamics can also be applied to ship dynamics. So, these are mechanical engineering and marine engineering. In these fields, we are more particular about this. Aerodynamics, and we try to discuss the forces and moments experienced by a body. When I say immersed in a fluid stream, in the air, the airplane is immersed in a fluid stream.

When a body is placed in a fluid stream, it experiences force and moment. When we consider a body in space, we observe these forces. For example, there is a lift force that acts upward—lift force, right. Then there is a drag force, right, which pulls backward—drag. If you take a car, there is a drag force.

So, drag force. Lift force—this lift force acts against gravity. When discussing lift force, you also observe a moment around the lift, called the yawing moment. There is a moment along the axis of the drag force. When rotated, it is called the rolling moment, and then there is a pitching moment. If you examine this figure more carefully, the blue boundary we have drawn represents an arbitrary body. So, there is an arbitrary body moving against the air. This is called the free-stream velocity V. It flows around the velocity. Now, there are three phenomena.

So let us try to take in a free space. A body is moving. So the body will first try to go up in this direction. That is called the lift force. And there is a free-stream velocity coming. There is a pull back. That is drag. Then there is a force called pitching. So, these are the three forces, right? So, when we try to see—if you have a hand, which is the same phenomenon common in robotics—you will have a pitch, right, a roll, and a yaw. This is called yawing.

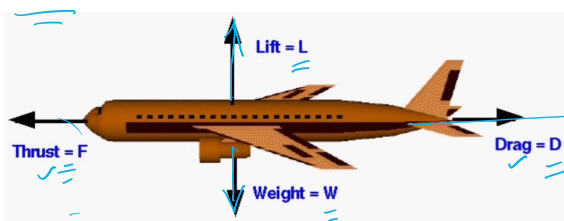
Drag force. The primary forces are drag force and lift force. So drag force: the force on your body parallel to the free stream. So I said it moves like this. There is a velocity going. So there is a force on the body parallel to the free stream and positive downstream. It is essentially a flow loss that must be overcome by the body to move against the stream. So what we are trying to say is there is a body moving. There is a velocity coming. This velocity is trying to pull back.

So you have to beat this velocity and move forward. So that force is called a drag force. The stream is nothing but the free stream velocity of air. Next is lift: a force that is perpendicular to the drag. So, this is a drag force perpendicular to the drag force. So, lift acts against gravity. So, here is gravity, right? The force perpendicular to the drag often performs a useful task like supporting the body's weight. This is the lift force. So, when a body is immersed in a fluid, you will have two forces: drag force and lift force. Friends, if you take it as a point, it will be easy to solve.

When you take it as a line, then it is a little complex, but you can try to solve it. When you take it as a plane, then you will have a little more complexity to solve. A point is defined in x, y, z, x0, y0, z0. When you take it as a line, it will be x0 and x1. When you take it as a plane, it will be x0, x1, x2, and x3. So it will be a plane. And no body that floats in the air is flat. It will have its shape. So now you see how the complexity increases step after step. So finding out the drag force and lift force for a plane, for an automobile car, for a moving ship, or for a submarine is a challenge. But it is all derived from simple basics.

Aerodynamics

- **Weight**: It is a force that is always directed toward the center of the earth. The distribution of the weight and the center of gravity also changes.
- **Thrust**: To overcome drag, airplanes use a propulsion system to generate a force called thrust. The direction of the thrust force depends on how the engines are attached to the aircraft.



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https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/thrust-to-weight-ratio/ 5

Weight: it is a force that is always directed downward toward the center of the earth. The distribution of weight and the center of gravity also change. So this is the lift force, and this is the weight force. So lift is represented by L, weight is represented by W, drag is represented by D, and thrust, which is there, is represented by F. So what is thrust?

So when there is a force which is pushing this body behind, so then you get the thrust force which moves forward. Right. So that is why if you see in the fighter plane, when it goes very high speed, it will release a jet of air. When you look at the sky, you see a straight line there because the air is released. The combustion gas is released into the atmosphere with very high velocities.

So it is not able to diffuse very fast. Over a period of time, it gets diffused. So that is given for the plane to move, that is called as a thrust force. The fourth force, which is going to be there, is the thrust force. To overcome the drag, the airplane uses a propulsion system to generate a force called thrust.

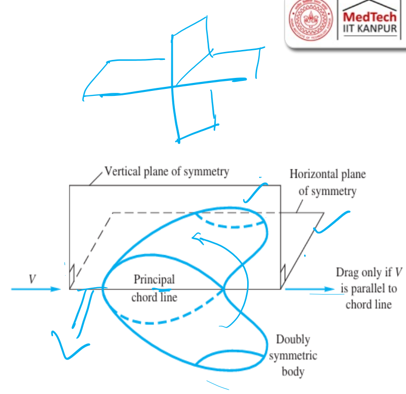
The direction of the thrust force depends on how the engines are attached to the aircraft. It can be on the wings or the tail, depending on your requirements. And if you look at the boat, when you are trying to go by a rowing boat, you will have a controller at the back. So you can try to change the direction of the boat by adjusting the position of the flap at the back. Similarly, in a plane, you can control the direction of motion to some extent by changing the thrust force exit and wing direction.

So the four forces that come into existence are drag force, lift force, thrust, and weight. Four are there. Now you should understand that if a plane has to lift 180 people, it must generate sufficient lift. Then you should understand what the thrust will be. It will be phenomenal.

The lift opposes the weight. Then it has to not only lift but also push it forward with the thrust force. Now, friends, think of an engine that is there—how much thrust force it has to produce for a plane to fly. In a ship, it is the same story.

Aerodynamics

- If the free stream is parallel to the intersection of vertical and horizontal plane, then it is called as the principal chord line of the body.
- The body experiences drag only, with no lift, side force, or moments.
- The body will have an asymmetric orientation and all three forces and three moments can arise in principle.



If the free stream is parallel to the intersection of the vertical and horizontal planes, then it is called the principal chord line of the body. So, you can see here—this is the vertical plane, the stream symmetry of symmetry. This is the horizontal plane of symmetry. This is like the x and y axes. So now what are you doing is you are extending it, right? You have a paper, now this paper is opened. That is all. It is almost like this. So, this is the vertical plane of symmetry, and this is the horizontal plane of symmetry.

So, your body is there. So, you can see here—this blue one is the body. So, this body, whatever is there, is trying to get moved. So, if the free stream is parallel to the intersection of vertical and horizontal plane, then this one is called as the principal chord line. So, this is a body—this is the body which is also there—and this line is called the principal chord line, right.

So, this is a body. So, the body is trying to swing. So, you can see here, this is the doubly symmetric body. So, this one, which moves to this question. The body experiences drag only, with no lift, side force, or moment.

The body experiences only a drag force. Friends, what you do in analysis for a plane, and what you do in analysis for your car, is completely different. Because the car is supported by a road. So the car need not have the lift factor at all. And the weight, whatever is there, is resting on the road.

So now, what is more important is the drag and the thrust. So that is what we are trying to explain here. The body experiences only drag, with no lift, side force, or momentum. So this is not there, this is not there for a car, and this is also not there for a car. So it is only this way. The body will have an asymmetric orientation, and all three forces and three moments can arise in principle. This is an important point.

Fundamental Laws of Aerodynamics

Bernoulli's theorem

- Bernoulli's theorem is a fundamental relation in fluid mechanics, named after Daniel Bernoulli, who published a hydrodynamics textbook in 1738.
- **It states the fundamental relationship in fluid mechanics that connects pressure, velocity, and elevation in a flowing fluid.**
- The theorem is often derived from integral relations for a control volume or by integrating Euler's equation along a streamline.

Assumptions

- Viscous effects are assumed negligible.
- The flow is assumed to be steady.
- The flow is assumed to be incompressible.
- The equation is applicable along a streamline.

So the fundamental law of aerodynamics began with Bernoulli's theorem. Bernoulli's theorem is a fundamental relationship in fluid mechanics, named after Daniel Bernoulli, who published a hydrodynamic textbook in 1738. It states the fundamental relationship in fluid mechanics that connects pressure, velocity, and elevation in the flowing fluid.

The theorem is often derived from the integral relationship for a controlled volume or by integrating Euler's equation along a streamline. We saw what a streamline and streakline are. So what are the assumptions here? The viscous effects are assumed to be negligible, which is not the case in air. In an airplane, the air density changes, and the viscous effects also change.

The flow is assumed to be always steady. The flow is assumed to be incompressible. The equation is applicable along a streamline. So these are the assumptions. These assumptions are major assumptions. In reality, today we are trying to ease out one or the other assumptions, and we are trying to solve the problem.

Bernoulli equation:

$$\frac{p_1}{\rho} + \frac{1}{2}V_1^2 + gz_1 = \frac{p_2}{\rho} + \frac{1}{2}V_2^2 + gz_2 = \text{const}$$

- p: Pressure at a specific point in the fluid (Pa)
- ρ: Density of the fluid (kg/m^3)
- V: Flow velocity at a given point (m/s)
- g: Acceleration due to gravity (m/s)
- z: Elevation (height) at a specific point (m)

So the Bernoulli's equation is represented in this way, where you have P is the pressure. This is pressure, this is density. V is the flow velocity at any given point of time, g is the acceleration due to gravity, z1 is the elevation height at a specific point. This is the initial point, this is a final point, and it is said to be a constant.

Continuity equation

- The continuity equation is a fundamental principle in fluid mechanics that expresses the conservation of mass for a fluid flow.
- It is considered the local mass balance equation, derived by considering the limit of a vanishingly small control volume or fluid particle.
- The equation was formulated by Euler in 1757 .The general equation is given by:

$$\partial\rho/\partial t + \nabla\cdot(V) = 0$$

where,

- ρ is the density,
- t is time,
- V is the velocity vector,
- ∇ · is the divergence operator.

The continuum equation, which is used here, the continuum equation is a fundamental principle in fluid mechanics which that expresses the conservation of mass for a fluid flowing. It considers a local mass balance equation derived by considering the limits of vanishingly small control volumes or volumes. Fluid particles. So, it is simplified. So, Euler in 1757 gave this general equation, which is $\partial\rho/\partial t + \nabla\cdot(V) = 0$. So, this divergence operator we can get while solving problems.

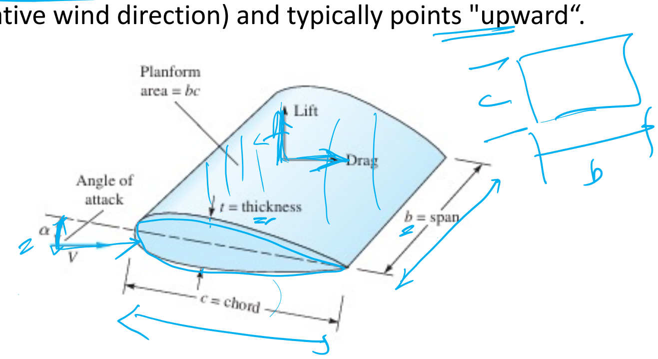
Lift

- Lift is a fundamental aerodynamic force experienced by bodies immersed in a fluid stream.
- It is defined as the resultant force component that is normal to the direction of the flow at infinity (or the relative wind direction) and typically points "upward".

$$C_L = \frac{L}{\frac{1}{2}\rho V^2 A_p}$$

Where,

- C_L is the Lift coefficient,
- L is the Lift,
- ρ is the density,
- A_p is the area (b*c).



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Lift: when we talk about lift, this is the typical aerodynamic profile. This is called an aerofoil. It is not a flat plane. It has a curved surface, right? Aerodynamic. It is called an aerofoil. Okay. Lift. The lift is a fundamental aerodynamic force because it lifts up. It is experienced by the body immersed in the fluid stream. It is defined as a resultant force component that is normal to the direction of flow at infinity and typically points upward.

So, it is defined as a resultant force component that is normal to the direction of the flow at infinity. So, the normal to this drag direction is the lift. Typically, it is always measured upward, and when the plane moves this way or that way, the lift angle changes.

So, it is given by the equation CL, which is nothing but the lift coefficient:

$$C_L = \frac{L}{\frac{1}{2}\rho V^2 A_p}$$

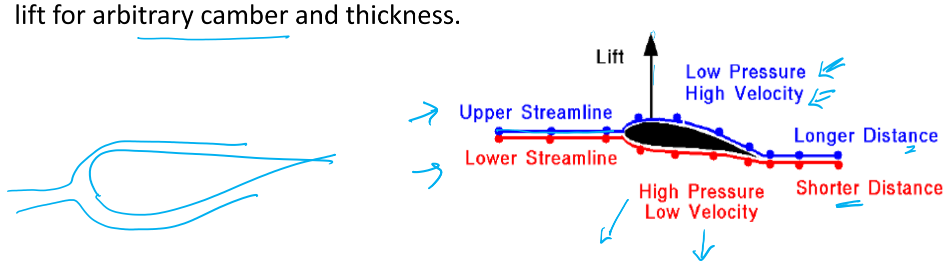
Ap is the area, which is calculated as b*c. Again, friends, here we are calculating BC, which is just assumed to be a flat plate. So, this is trying to calculate the area B, and this is going to calculate the area C.

But in reality, you have a curved surface. So, the lift coefficient we find is a generalized one. So, if you see here, the thickness of the airfoil profile is given as T. And whatever the width is—if you say B is the span width of a plane, this is the width of a wing. So, that is B. And the thickness is—suppose if the plane is going like this, you have a wing. This is the thickness.

And then there is your chord length C. So the plane form of the area BC will be this. This one is the plane form, and the air always tries to hit at the velocity like this. And there is an angle, which is called the angle of attack, alpha. So this is very important. The angle of attack alpha tries to decide how you get the lift when it goes up. So alpha is a very important parameter. This is called the angle of attack.

Lift

- Lifting bodies (airfoils, hydrofoils, or vanes) are intended to provide a large force normal to the free stream and as little drag as possible.
- The first theory of lift was proposed by Frederick W.Lanchester.
- Modern airfoil theory dates from 1905, when the Russian hydro dynamicist N. E. Joukowsky (1847–1921) developed a circulation theorem for computing airfoil lift for arbitrary camber and thickness.



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The lifting bodies (airfoil, hydrofoil, or vanes) are intended to provide a large force normal to the flow stream and as little drag as possible. So, if drag is reducing, the resistance is reducing.

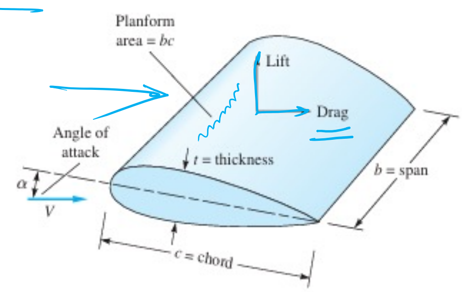
If the resistance reduces, you will get a higher velocity. So this is the lift; this is the upstream. So you have an aerofoil, which comes like this, called the upstream, and which goes like this, called the downstream. So, upstream and downstream. So now, this is the airfoil profile, and the lift is always in the upward direction. So, above the plane, you will have low pressure and high velocity; below, you will have high pressure and low velocity. So, the upstream travels a longer distance, and the downstream travels a shorter distance. This creates the lift. So, the lifting body, or aerofoil—the same principle applies to a ship as well. Now, we are discussing a plane, but the same applies to a ship.

But the upstream and downstream distances may be equal or vary. Lifting bodies are designed to provide a large force normal to the free stream with minimal drag. Because drag is the resistance. The first theory of lift was proposed by F. W. Lanchester. Modern aerofoil theory dates back to 1905, when Russian hydrodynamist N. E. Joukowski developed a circulation theorem for computing aerofoil lift for arbitrary camber and thickness. He developed this, and it came into existence. So, in 1905, the theory was established.

Drag

- Drag is one of the primary forces experienced by a body immersed in a fluid stream.
- It is defined as the resultant force component on the body that is parallel to the free stream direction and points positive downstream.

$$C_D = \frac{\text{drag}}{\frac{1}{2}\rho V^2 A}$$



Where,
- C_D is the Drag coefficient,
- ρ is the density,
- A is the area (b*c)

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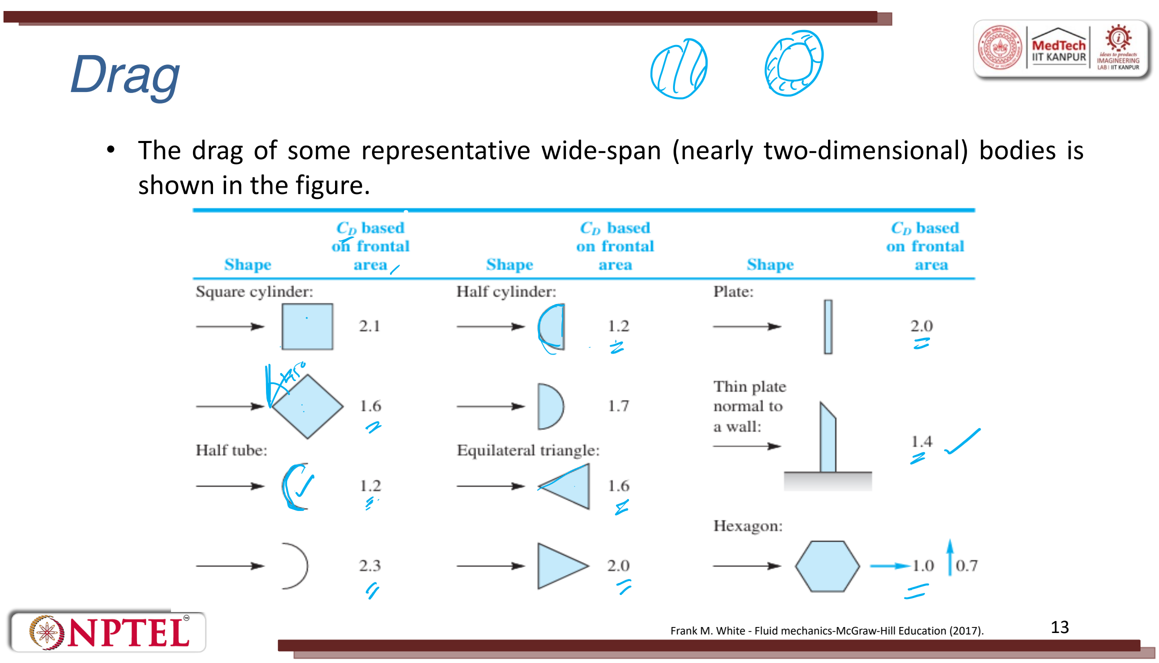
The next force is the drag force, right? The figure is the same. The only difference to note is the drag force. Lift is this way in which the air is flowing in this direction or at an angle. So, this is the drag force. Drag is one of the primary forces experienced by a body immersed in a flow stream. So, if you have undulations on this, you might have a lot of air resistance, and if the undulations are very small, then there is a possibility the smooth streamline of air, whatever is there, is broken. So, you can have it as an advantage.

It is defined as the resultant force component on the body that is parallel to the free stream direction and points positively downstream; this is the drag force. The drag force or the drag coefficient can be figured out by Cd,

$$C_D = \frac{\text{drag}}{\frac{1}{2}\rho V^2 A}$$

A is b*c, as we have already seen. So basically, what you do is you have a drag coefficient, which many times is given in the examination, and then you will try to multiply by this factor, which I call x. x is equal to drag. So through this, you can try to find out what your drag is. So in the previous one, we saw lift almost the same way.

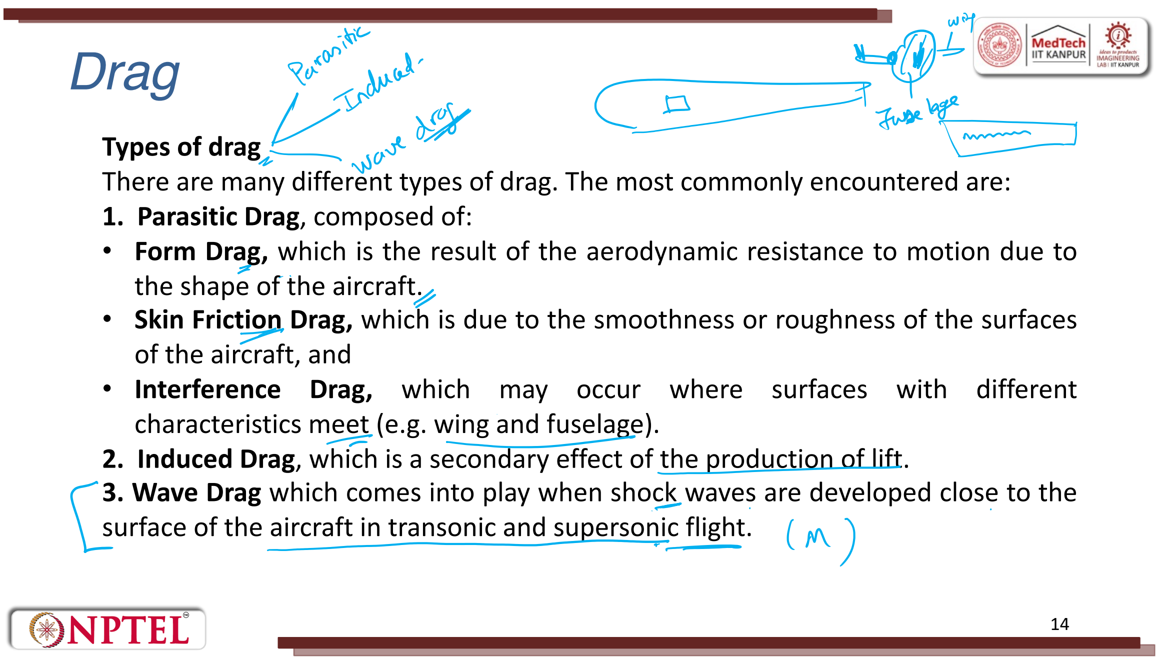


So, the drag of some representative wide-span, nearly two-dimensional body is shown in the figure. For a square cylinder, for a diamond-like cylinder, the square is rotated by 45 degrees. So, for example, this is rotated by 45 degrees. You get the Cd value lower. What is Cd?

CD is the coefficient of drag. Then, if it has a half tube, it is 1.2. When it has a convex shape or the inverse of a half tube, you see 2.3. So now, just by changing the shape, you will try to see how the CD on the frontal area changes. Now, if you try to have a half cylinder, you see it is 1.2, which again I just changed; that is why you see the values are very low. So, if you have a closed cylinder or a half tube—cylinder is full solid, tube has an internal diameter and external diameter—you see. So now, in an aeroplane, whether you have a solid or a hollow tube, the CD is almost constant. So, it is better to have reduced weight. So, we always go for hollow tubes, right? Then, if you have an equilateral triangle, it is 1.6.

So, if you see here, this one at an angle of 45°, it represents the same. So, it is 1.6. So, rather than having a square, you can have a rectangle. When the surface area is large, you see it is 2. When we try to have a plate-like structure, it is 2. Plate, why? Plate is very important because in the wings, if you have a vertical wall, it is like a plate.

So, then thin plate. Normal to the wall is 1.4. This was 2 is this way. This is this way. So that is why in a plane you try to have this and this. When you have a hexagonal shape, it is 1, and here, hexagonal is very difficult to fabricate. So that is why we try to have this airfoil in this direction.



So, in drag, there are various types of drag, which are very important for you to understand. It is not one full force. Drag is of three types. One is parasitic drag. Then, you have induced drag. Then, you have wave drag. The wave drag, which looks like a wave—the recreating wave—comes into play when shock waves develop close to the surface of the aircraft in transonic or supersonic flights. It does not happen in one wave, which is normally seen in the ocean as well. So, that is what wave drag is, which comes into play when shock waves develop close. Shock waves are disturbances in the airflow, so that is called shock waves, which develop close to the surface of the aircraft, right? So, it operates at very high speeds, supersonic.

We discussed the Mach number, so in the Mach number classification, we have seen supersonic. So, then let us try to see the other two parasitic drags. So, it is composed of form drag, skin friction drag, and interference drag. Form drag is a result of aerodynamic resistance to motion due to the shape of the aircraft.

That is why we always try to shape a plane like this, and then you have a wing. Right. This is called form drag, depending upon the shape. Skin drag is due to the smoothness or roughness of a surface. So, this is what I said: you take a wing profile and then you have undulations on the surface—that is skin friction drag. If the skin friction is too high, then it is very difficult.

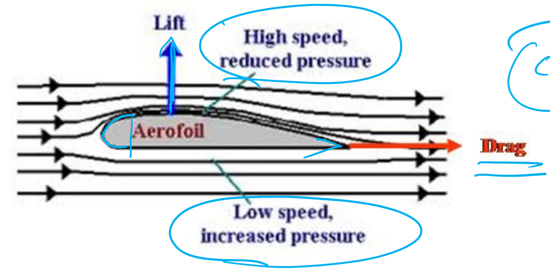
What happens? It gets integrated into the profile, and the wind blows above it or flows above it. This is due to the smoothness or roughness of the aircraft's surface. Interference drag occurs between form and skin, which may happen where surfaces with different characteristics meet, such as the wing and fuselage. The center portion is called the fuselage.

This is the wing, this is the fuselage, okay? Where they meet is called interference drag. So, form happens here. Predominantly, this is form, which happens here, and then the wing happens here or the skin happens here, then the interference happens here. The induced drag, which is a secondary effect of producing lift, is called induced drag. So, drag. All these things are resistance to flow.

So, you have to reduce as much drag as possible. So, you have form drag, skin drag, and interference drag. Then you have induced drag and wave drag. These are all normal drags, except for this, which is for high-speed flights.

Airfoil

- An airfoil is a type of lifting body. Airfoils are specifically designed to provide a large force normal to the free stream (lift) and as little drag as possible.
- Conventional airfoil design has evolved into shapes resembling a bird's wing, typically being relatively thin (thickness-to-chord ratio, t/c, is usually less than 0.24) with a rounded leading edge and a sharp trailing edge.

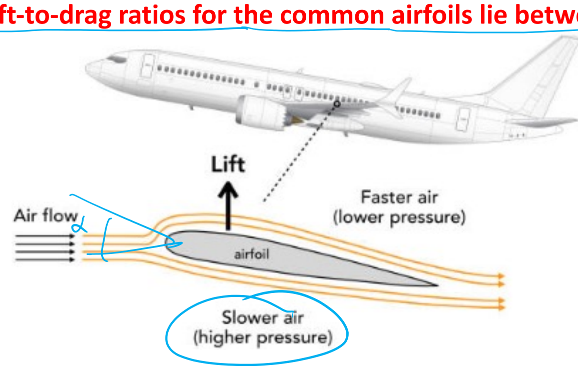


Let us look into the aerofoil. An aerofoil is a type of lifting body. It is specifically designed to provide a large normal force to the flow stream. So, it provides a normal force to the flow stream, which is lift, and very little drag. Drag is nothing but resistance. As I told you, on the top you will have high speed and reduced pressure, and at the bottom you will have low speed and increased pressure.

Conventionally, aerofoil design has evolved into shapes resembling a bird's wing, typically relatively thin, with a thickness-to-chord ratio. We saw what the chord is—this is the chord. Thickness is the T we saw, which is T by C, usually less than 0.24, with a rounded leading edge and a sharp trailing edge. So, this is an aerodynamic profile. You might have seen why we went for this. You have seen it through the CD coefficient. We saw why it has to be like that.

Airfoil

- A lifting craft cruises at low angle of attack, where the lift is much larger than the drag.
- **Maximum lift-to-drag ratios for the common airfoils lie between 20 and 50.**

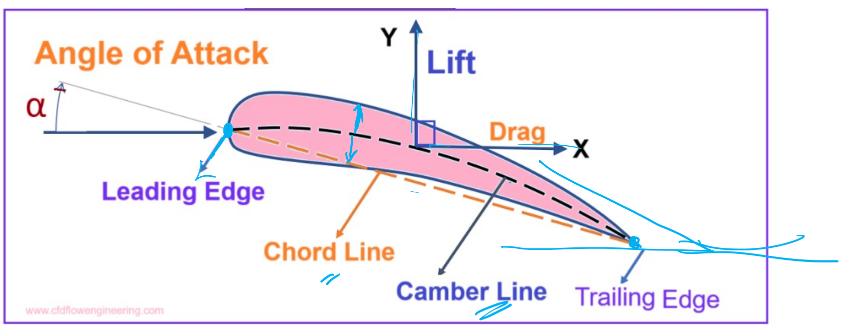


A lifting aircraft cruising at a low angle of attack. What is the angle of attack? Alpha, right? A lifting aircraft cruising at a low angle of attack where the lift is much larger than the drag. So, the maximum lift-to-drag ratio for a common aerofoil is around 20 to 50.

So, the ratio of lift to drag. 20 to 50 lift to drag. So, drag has to be as small as possible. Lift has to be as high as possible so that you get a higher value. So, when the plane goes like this, when it is trying to lift, you will see lift is on the higher side. Then you will see the air pressure; higher pressure of air is low. So, that will try to press, and this will try to go up.

Airfoil

The anatomy of an airfoil is given by:



https://cfdflowengineering.com/wp-content/uploads/2023/08/Basic-of-airfoil-schematic-diagram-1024x482.png 17

So, when we try to look at the anatomy of the aerofoil, this is the alpha angle of attack. This one is called the leading edge, trailing edge, lift, drag, chord line, which is the perpendicular. So, it is a straight line, chord line. And this is the deviation of a chord line, called the camber line.

So, these are all very important. When we try to take it for the car also, almost the same thing comes. So, there will be some modifications. But interestingly, in a car, you will not have a lift force, right? Drag force is dominant. So, when you go into water, it is again the same story, but the lift will be on the higher side and the submarine will try to go down.

Airfoil

- **Leading Edge:** The leading edge is the foremost point of the airfoil, the part that faces the oncoming airflow.
- **Trailing-Edge:** Located at the rear end of the airfoil, the trailing edge is where the airflow recombines after passing over and under the wing.
- **Chord Line:** The chord line is a straight line connecting the leading edge to the trailing edge of the airfoil.
- **The angle of Attack:** The angle of attack is the angle between the chord line of the airfoil and the oncoming airflow. Adjusting the angle of attack allows pilots to control the lift and drag forces acting on the airfoil, which is crucial for takeoff, landing, and maneuvering.
- **Camber Line:** The camber line is a curved line equidistant from the upper and lower surfaces of the airfoil. It is used as a reference to quantify the amount of camber present in the airfoil's design.

So, the leading edge: the leading edge is the foremost point of the aerofoil. The part is facing the oncoming airflow. Trailing edge: located at the rear end of the airfoil, the trailing edge is where the airflow recombines after passing over the top and bottom layer. This is the trailing. So, the stream comes here, the stream goes here, then it gets recombined. Chord line: the chord line is a straight line connecting the leading edge to the trailing edge of the aerofoil.

Leading edge to the trailing edge, connecting straight line. The angle of attack: the angle of attack is the angle between the chord line. This is the chord line, right, between the chord line of the aerofoil and the incoming airflow. So, you saw a chord line like this and there is an airflow. So, this is alpha. Adjusting the angle of attack allows the pilot to control the lift and drag force acting on the aerofoil, which is crucial for takeoff, landing, and maneuvering.

So they always try to talk about the angle of attack, right? So camber line: camber line is the curved line, this is a curved line, is a curved line equidistant from the upper and lower surface of the aircraft. So, this is the camber line, upper and the lower, right.

It is equidistant from the upper and lower surface of the aerofoil, which is used as a reference to quantify the amount of camber present in the aerofoil design. So, these two are very important: camber line and angle of attack. There are transient stages in the development of lift. So, I have classified it as A, B, C and D. So, A is startup where the rear stagnation point of the upper surface is there and there is no lift at all. In B, there is a sharp trailing edge induces separation between the top and the bottom and there is a small vortex which is created which creates a slight lift.

So, the starting vortex is shed and streamlines flow smoothly from trailing edge. The lift is now 80% developed. So it is almost lift is 80% developed. The large vortex shed far behind the trailing edge, now very smooth, the lift is fully developed. So, now you see the vortex, how it is getting, and how the vortex is moving.

Airfoil

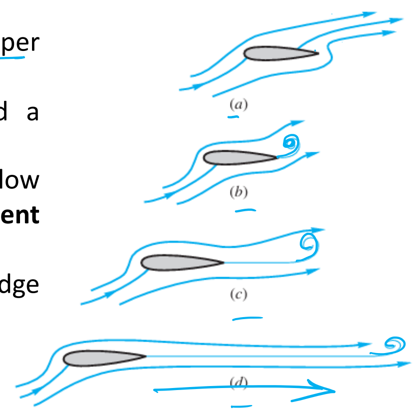
Transient stages in the development of lift:

(a) start-up: rear stagnation point on the upper surface: **no lift.**

(b) sharp trailing edge induces separation, and a starting vortex: **slight lift.**

(c) starting vortex is shed and streamlines flow smoothly from trailing edge: **lift is now 80 percent developed.**

(d) starting vortex now shed far behind, trailing edge now very smooth: **lift fully developed**.

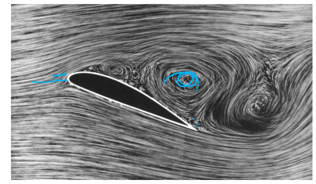


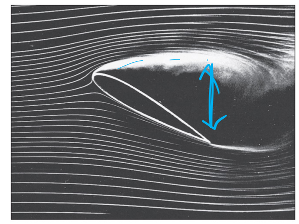
Frank M. White - Fluid mechanics-McGraw-Hill Education (2017).

So, these are the transient stages. So, here in A, there is no lift, it is at normal, slight lift, there is a vortex behind the trailing edge, then there is this trailing edge is going back, so there is a lift getting developed 80%, and fully developed lift is, the vortex is very far behind.

Airfoil

- At a low angle of attack, the rear surfaces have an adverse pressure gradient but not enough to cause significant boundary layer separation. The flow pattern is smooth, as, and drag is small and lift excellent.
- As the angle of attack is increased, the upper-surface adverse gradient becomes stronger, and generally a separation bubble begins to creep forward on the upper surface.
- At a certain angle $\alpha = 15^0$ to 208^0, the flow is separated completely from the upper surface. **The airfoil is said to be stalled: Lift drops off markedly, drag increases markedly, and the foil is no longer flyable.**





So, at a low angle of attack to the plane, the rear surface have an adverse pressure gradient. At low angle of attack, alpha, okay, the rear surface have an adverse pressure gradient, but not enough to cause significant boundary layer separation. The flow pattern is smooth as and the drag is small and the lift is excellent when it goes like this angle of attack, at a low angle of attack.

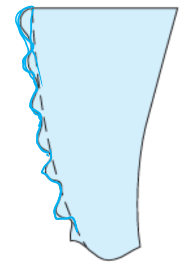
When the angle of attack increases, when alpha increases, the upper-surface adverse gradient becomes stronger. Generally, a separation bubble begins to creep forward on the upper surface as the angle of attack increases. The angle of attack generally takes a value between 15 to 20. The flow is completely separated from the upper stream. The aerofoil is said to be stalled. The lift drops off markedly, drag increases markedly, and the aerofoil is no longer flyable.

Okay. So, this is what they are trying to talk about. So, you see a vortex getting created. Then, when the angle of attack increases, the upper-stream adverse gradient becomes stronger, and generally, a separation bubble forms. So, the application of aerofoil—we always think the aerofoil is smooth, but in reality, if you look at whales and sharks, they always have some undulation on the surface.

Application of Airfoil

A Wing Inspired by the Humpback Whale

- Unlike most whales, the humpback whale has tubercles, or bumps, on the leading edge of its flippers. Scientists tested this idea, using a standard wing with periodic bumps glued to its leading edge.
- They report a 40 percent increase in stall angle, compared to the same wing without bumps, plus higher lift and higher lift-to-drag ratios. The concept has promise for commercial applications such as wind turbine blades.



New experimental airfoils: plan view of a wing modeled on the humpback whale flipper

D. S. Miklosovic et al., "Leading Edge Tubercles Delay Stall on Humpback Whale," Physics of Fluids.

So, the wings are inspired by the humpback whale. Unlike most whales, the humpback whale has tubercles or bumps on the surface of the leading edge of its flipper. The flipper is what is there in the projection. Scientists tested this idea using a standard wing with periodic bumps glued on its leading edge. The report says that there is a 40% increase in the stall angle compared to the same wing without bumps. So, the lift-to-drag ratio increases. The concept comprises commercial applications such as wind turbine blades, which are made with these tuber cells today. So, these are structures that are present. So, if you go back and see, we studied the drag, which is skin friction drag. So, that is reduced to a large extent by doing so on the surface.

To Recapitulate

- What is Aerodynamics?
- State and define Fundamental Laws of Aerodynamics.
- What do we understand by the term "Lift"?
- What is Drag in Aerodynamics?
- Define Airfoil stating its applications.

Friends, in this lecture, we saw what aerodynamics is. Then we saw the fundamental law of aerodynamics, Bernoulli's law. We understood what lift is, what drag is, and what airfoil shaping and its application are.

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These are the references we followed for preparing this lecture. And thank you very much.