Optimal Control, Guidance and Estimation

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Lecture No. # 15

Optimal Control, Guidance and Estimation

Overview of Flight Dynamics – I

This particular lecture, we talk about some basic introduction of atmosphere, atmospheric flight mechanics. There is nothing to do with too much extensive detail, I mean, the, this is a course by itself, we will talk about many, many details of that, but I, I assume, that many people who, who study this course may not be knowing anything about flight mechanics, for them it becomes a small introduction of basic principle, how things fly actually. Then, later on, we will see some of the equations involved in that and how to manipulate that using control system theory, that, that connection will be done later, for this particular class, we will just, just see some, some basic principles of flight mechanics.

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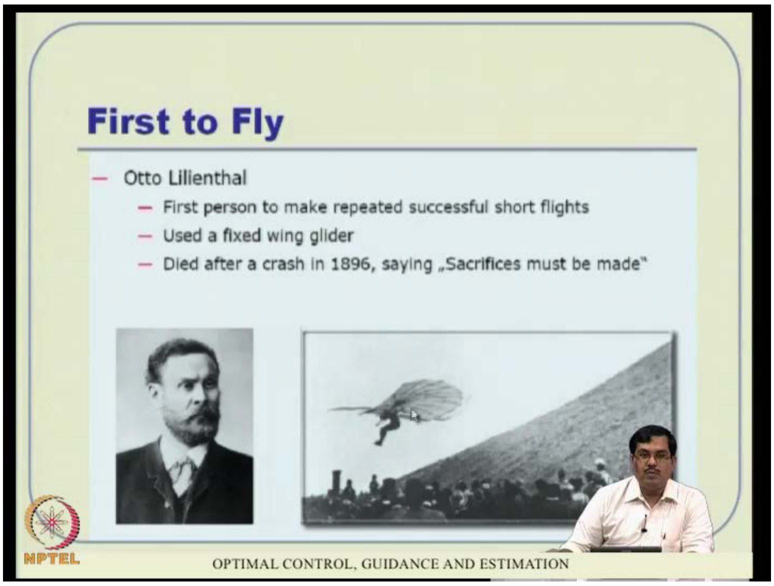

First of all, there are various air craft designs. If you see, first to fly probably goes to this particular gentle man here, his name is Otto Linienthal and he, actually, the 1st person to make repeated successful short flights. So, he kind of, many things, the parts other things, he attempted that actually, and essentially used a fixed wing glider and then, obviously, died at in a crash in 1896. And purposefully, he knew, that the risk involved and he kept on saying, that sacrifices must be made in that, (( )) is the first person to attempt fly like a bird.

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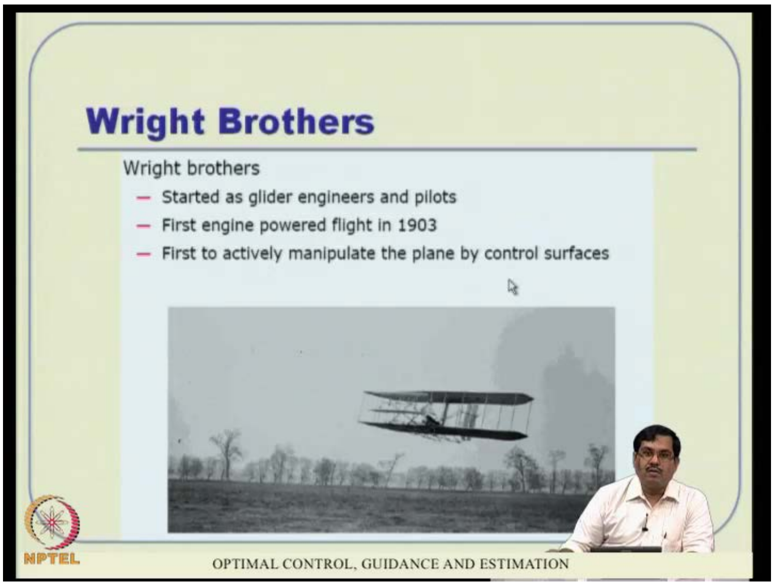

Then, the, obviously, we all know, that the next big credit goes to Wright brothers, and they started as glider engineers and later on pilots as well. They did lot of internal testing, followed by optimization and things like that of the wing structure, and things like that. However, the, the most credit for this Wright brothers' successful flight goes through the control surfaces. Actually, that means, then, they are the 1st person to realize, that uncontrolled flights are simply not possible; you need to have a control system for successful flight actually. So, that is, that is the reason, probably, why they were successful where others were not successful.

It is also the 1st engine powered flight in 1903, just about 100 years back, 100, 105, 106 years back, within that tremendous improvement in this field. Remember, just about 105 years back, now body knew how to flew, there were all surface transport only, but air transport was not there, actually.

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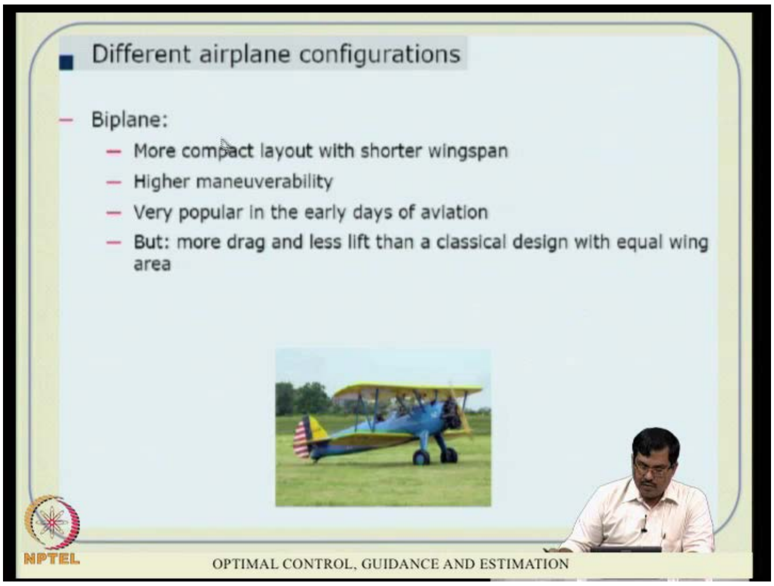

Now, after that, you can, will skip, skip a gap of about 30 years probably, then we will go little bit to the modern era. This is something, which people started, what is called as biplane. You can see, that there are 2 wheels here, 1 bottom and 1 on top, though that essentially, creates an additional lift to support your structure actually, at the expense of little bit additional weight also, by the way, because the most structure you have to the system, the weight becomes more, as well, it, it had high maneuverability.

It was very popular in the early days of aviation actually. So, I mean, sometimes people even used these for, for war applications, in world war actually.

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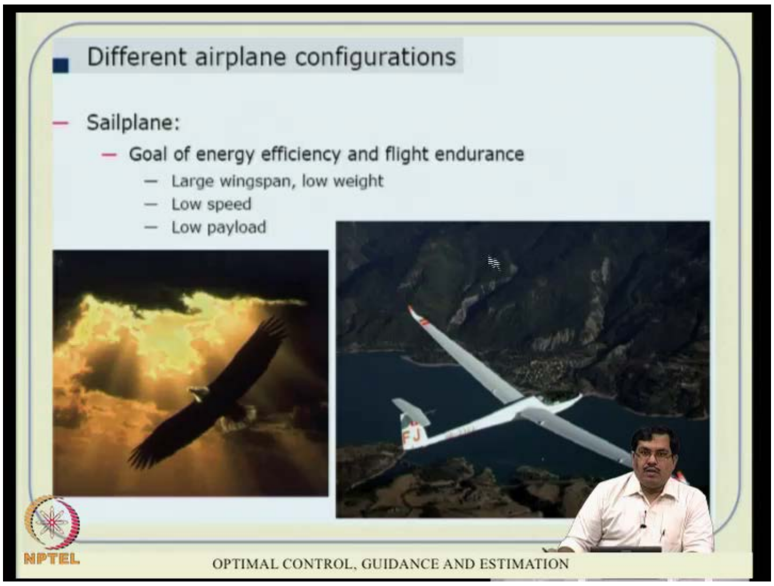

Then, there are other applications, there are other many, many designs has come up with over the period of time. The next thing probably, you can see is this is a very long wing, essentially mimicking an eagle flying; if you have eagle flying, I mean, there, there is, you can constantly do that, this is something called high aspect ratio. That means, that the wingspan is very long, in case, I mean, it is as, it is very efficient wing in that sense actually. However, it cannot fly at low altitude and things like that, it has to fly at relatively high altitude and it has low speed, it can also take low payload actually.

So, there are like various consideration point of view, people will use many, many different things, this is, I mean and this is, just what I give here is just a small wing of things, actually largely collected from internet. So, that is part of it.

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Then, coming to the commercial aircraft, this is the, the best possible aircraft available in market today, commercial aircraft, the Air Bus 380; the strong competitor is from Boeing Dreamliner being designed, it is not yet in service, but this is in service. So, what are the aspects that you are looking for in commercial aircraft? You look for something like high lift versus drag ratio, that is invariably there in all aircrafts by the way, but the moment your lift to drag ratio becomes more and more, your efficiency of flying, the efficiency of aircraft design is higher, actually.

So, then, in addition to that, you also look for high fuel efficiency, high reliability and safety requirement. You carry out so many passengers here on regular bases, so you cannot compromise on safety issues and also, remember these are all long flights as well, actually. So, you really require good handling quality so that pilot can fly it in a good way, whatever he expects the, the aircraft response that way, and then there is a strong requirement for passengers comfort as well.

So, the too much of aberration, too much of oscillations at the end are not required out here. All weather operational capability is a requirements for, for airline operation (( )) operations and all that. And however, you remember the speed and agility or what you know as, what is known as maneuverability, are not that critical out here. Actually, you can nicely take off, go, land and as long as you are, maintain safe, safety requirements and passenger comfort, good handling quality and things like that and then, you are very much o.k. And on top of that, you have to assure, that the aircraft design is efficient with good engine quality also, like fuel efficiency has to be very good here.

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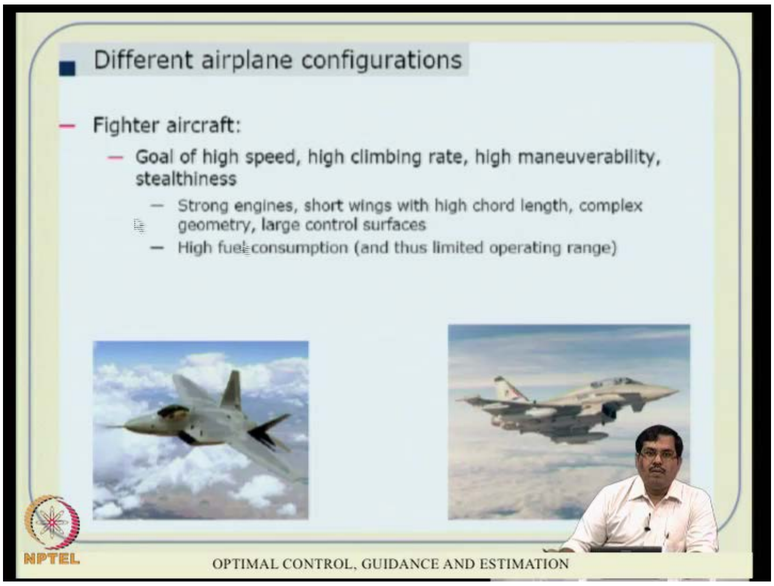

Then, coming to the next class is a fighter aircraft. There is a slightly goal reversal out here, what you really require is high speed, high climbing rate, high maneuverability, stealthiness and things like that, actually. So, here, efficiency is not that much important actually. If I, if I require, I can pay a little bit extra money, for, for may come back to superiority because I have to overpower than me; for that, I require all this actually. So, then, these are typically characterized by, characterized by very powerful engines, where short wings, high chord length, complex geometry, large control surface, because you really require high maneuverable, I mean, high maneuverability, that means, high control and things like that, high fuel consumption is also there and hence, it, it has some limited operating ranges as well, remember, it cannot carry heavy amount of (( )).

So, all these limit operations. So, there are concepts like, I mean, refilling the aircraft too, on the fly, that is, as it flies, it can be as well, fuel actually from a oil tanker and things like that, actually.

So, there is complete row reversal here; compared to commercial aircraft to fighter aircraft, commercial aircrafts are purposefully defined with, designed to be very stable and kind of, robust application requirements, things like that. Here, it is purposely made unstable and control, surface control design makes sure, that you, you, the, I mean, the closely system becomes stable, (( )) unstable actually here.

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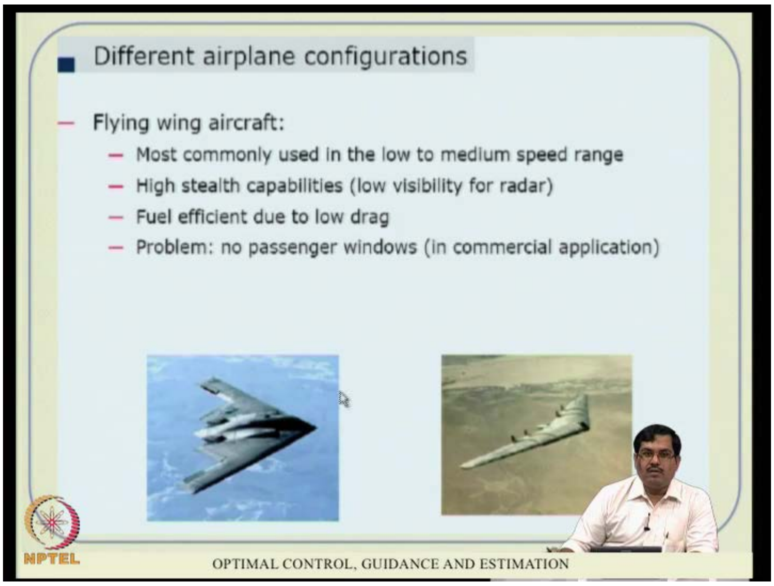

Then, there are various others, other designs; this is something called flying wing aircraft. That means, you can visualize the entire thing as a single wing and these are all requirements from stealthy considerations, actually. It has high stealth capabilities, that is, low visibility radar, fuel efficient, which is also fuel efficient due to low drag that typically flies at very high altitude.

So, the air density is very low, (( )) is low, (( )) will see that, this little couple of slides later. And normally, I mean this is typically not very popular for commercial aircrafts because there is no window arrangement here, people do not like to sit in a, kind of a, blind world, I mean, without looking outside, they cannot just want to, I mean, they do not, normally do not want to sit in a dark room, sort of, things actually So, that is not very popular among passengers.

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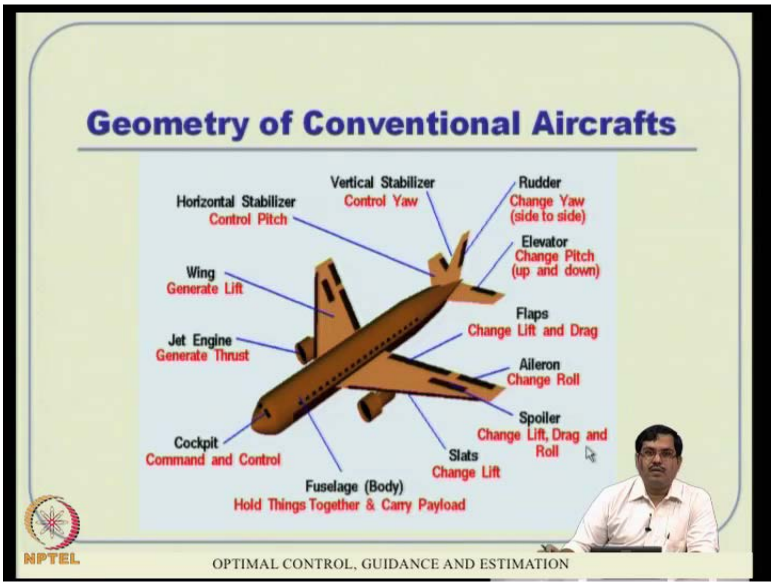

Actually, now coming to the conventional aircrafts geometry, if you see the aircraft geometry, there are various, various parts of the aircraft, that is, specific requirements actually. It is a complex system of course, it is, first of all engines, which is required for propulsion; it has a huge fuselage sort of thing, where people can sit or move around and things like that, that is, the people sit; 2 wings here, it is largely responsible for this, generating lift and there are…; then, there are a, like cockpit here, where the passengers, I mean, pilot sits and there are all lot of instrumentation out here, and after that, there are a lot of control surface arrangement actually. So, this is something called, this particular wing is the vertical stabilizer, this is horizontal stabilizer, the entire thing and then, within that, there will be like cut-outs here, which can actually deflect left and right, actually that way.

If you see this particular thing, it can deflect left and right; this particular thing, it can deflect up and down and thing like that itself. So, then, there are other arrangement, like what is called as spoiler slats and there are ailerons, there are like flaps out here and thing like that; there are huge number of control surface, that goes on here essentially as, as part of part of the wing or vertical, horizontal stabilizers, and there will be cut-outs, which can move perpendicular down or left and right actually, so through that the control movement gets generated and now, how it is done, we will see that actually here.

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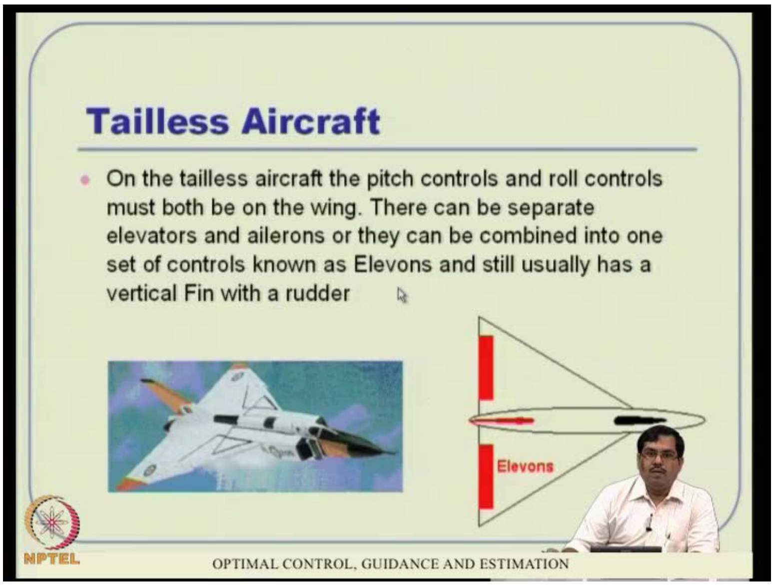

Coming to a different class, there is a tailless aircraft. What you see here is, is a complete tail arrangement actually, there is a horizontal stabilizer, this is vertical stabilizer out here, but in this one, there is no such arrangement and no wing. See, if you go there, there is clearly, there is a big wing and there is a tail arrangement here, both of the things, both of the things kind of coupled out here actually, they are put it, put it together for, for various, various reasons and one of that, it is, we have typical aircraft are typically supersonic.

So, the shock wave will get generated and all that, that is, should not treat the wing actually, it should go outside the wing. So, the, once the shock is generated here, it, it will something will like this actually, it will go outside the wing, it will not touch it actually, anyway.

So, that is one reason of that; there are other reasons as well actually. What happens here is the pitch control and roll controls, that is typically done through, the pitch control is done through the elevator control and roll control through ailerons, that are done together out here, what are called as elevons actually. If they differentiate, if, if they are reflected in a symmetric way, that is always an elevons; that, if they are deflected in asymmetric way, that is, one up and one down, then there is always elevons as well, actually. So, that is, that is the reason for what is called is elevon plus elevator, the elevator plus elevons, that is, elevons actually.

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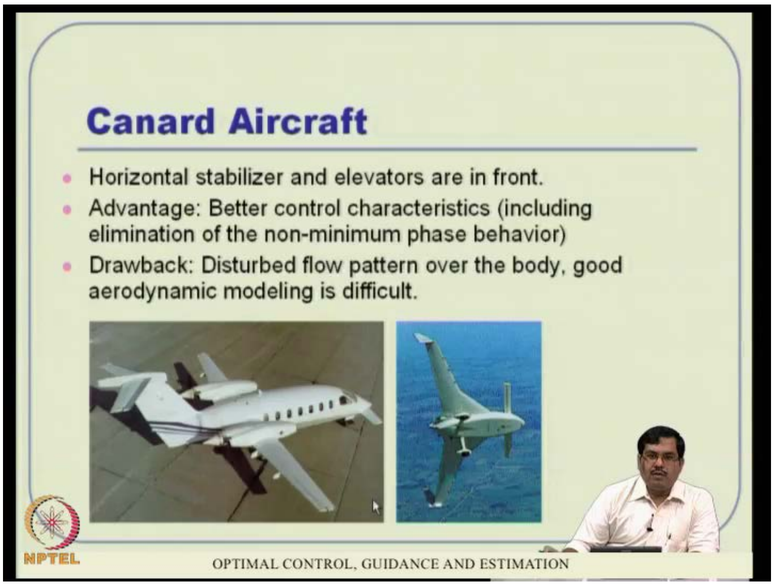

So, there are various variety of things, another thing, that has people have attempted is something called Canard configuration. That means, instead of a, a wing, I mean, instead of a control surface at the break, they want a control surface in the front actually, that is something called canard structure. So, again, inspired by some, some fish design and some, like some fishes have this structure actually, how, how they control there movement and all that, and some birds also have this.

So, what it essentially does? There is a horizontal stabilizer and elevators are kept in front, the advantage being better control characteristics. What happens here is, if you will see it later, that if you have a, if you have an elevator in the break, that actually creates a downward force. If you really want to go up, if you really want to go up, this, this need to be, I mean, you need to create force downwards, so that this entire, there is a movement upwards. So, the entire aircraft actually, kind of rotates upwards and then it generates lot of lift out here, that we will see mechanism of couple of slides down the line. However, that means, there is force, that creates, that is created downwards first here to rotate the aircraft in a, in a positive sense actually. So, that means, the, this entire body of the aircraft essentially, first goes down and then goes up, that is the nature of, what is called as, this non minimum phase system actually.

So, that is, kind of, (( )) because if you really want to go up, you create a force up, create a force up, so that the, if you create a force up, upward here, then there is a movement also upward, actually. So, then, there is no, no movement of going down and then going up actually, it simply starts going up and up and up actually, that you, you eliminate this non minimum phase behavior characteristics actually. However, a drawback actually, it, the, the flow on the aircraft gets distorted actually because see, if anything happens at the, at the tail, the actually, air flow is from the front to back actually, so anything that you do here, the flow disturbs and does not affect the body actually, it the flow on the body. But here it is not so, but it actually affects the flow on the body; that means, the aerodynamic modeling becomes difficult actually.

So, that means, your control characteristics will be good, but it will be working with a model, that, that does not have good fidelity. That means, you again compromise on that aspect actually. So, so, that is the, so, that is, there are various structures, that are available there, this is only a simple few glimpses of that actually.

Now, coming to how this, I mean, how these objects fly in the air. Now, let us see, that it, basically, there will be like force and movement balance actually. Now, let us know, what is force balance first?

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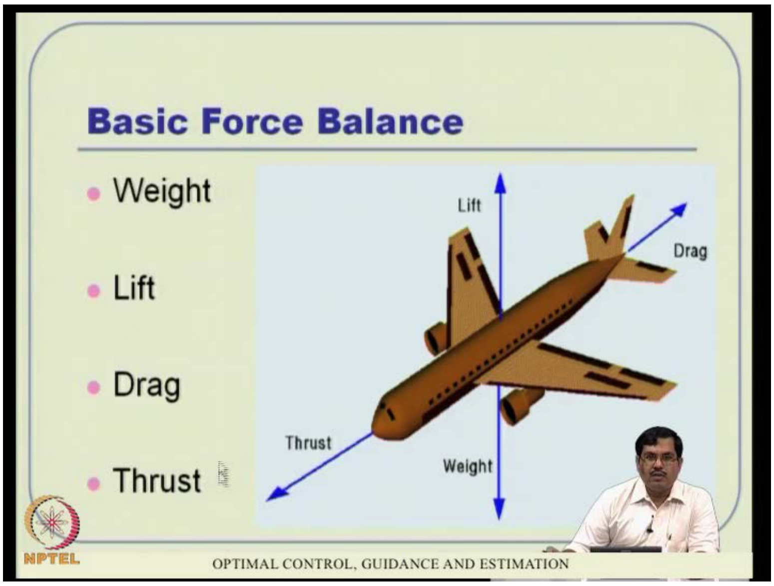

So, any flying object in a straightened level flight, let us say, tries to contract to this forces gets generated and balance each other actually. First thing is, there is a weight component, which is vertical. So, there must be a force, which is upward, which should contract that actually.

So, there is a weight, which is balanced by lift, for this lift generation mechanism also creates a drag. There are, there is, I mean, I will see, that reason for, the reason of drag, drag is a force to the break and hence, even if you want to go in a constant velocity, if constantly cancel out, this, this force, this drag force, that means, you really need a force to the front actually. So, there are 4 pressure actually in a straightened flight, one is weight, which is balanced by lift and then, there is a drag, which is balanced by thrust. So, you need to see how these forces are generated actually; weight is, obviously, it is very obvious, this is mass and then there is gravity, so because of that force is acting downwards. So, that is kind of obvious itself.

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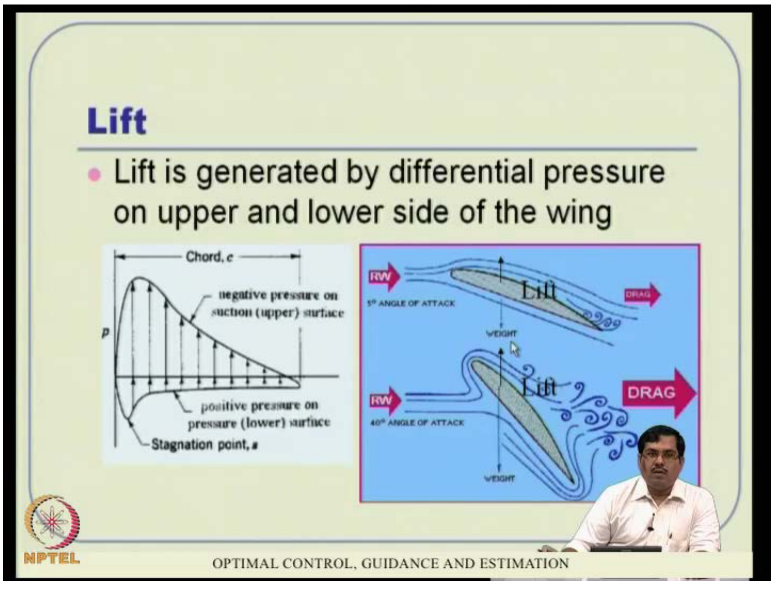

Let us see the other 3; 1st thing is, how do you counteract that by lift, how do you overcome effect of weight by lift? So, lift is generated by differential pressure on upper, upper and lower side of the wing actually. If you see the wing structures, there are variety of structures actually, if you see there and once the aircraft starts flying front actually, that means, you can visualize, that the, the fluid flows backward for the, this is one of the same things. Imagine a case, where aircraft moves to the fluid or fluid moves through the, through the body actually. Aircraft that is normally done in wind tunnel testing, also, the aircraft is kept stationery for the wind flown over, eventually, now essentially, what matters is relative velocity actually.

So, if you see, that the flow, it starts from left and goes to the right probably, and then, because of, there are the, this flow filled characteristics and all that, all details will be there in a dynamics book and things like that, we will not go too much into detail. What happens here is, because the, the way these wings are designed and you see, some sort of, something called angle of attack, let me say angle between the velocity vector and the mean chord line, because of that the flow pattern is different and hence, what happens is there is a low, there is a high pressure acting in the bottom and then there is a low pressure acting on the top, actually.

So, if you see, that there is a differential pressure actually, which builds on here and if you integrate over the entire area, what happens is, you get a force, net force upward, that is, that is what, what is lift actually. And remember, if this angel is larger and larger, this is a smaller angle, 5 degree angle of attack and this is actually a very large angle, 40 degree angle of attack. What happens is, you can get higher lift and optimal limit of force and after that, again this lift force start decreasing basically. So, essentially, what happens is, if you increase this, this angle keeping your speed constant, then you can increase the lift actually, but the price to it is your drag also becomes more and more high. So, so, that, that is the drawback actually.

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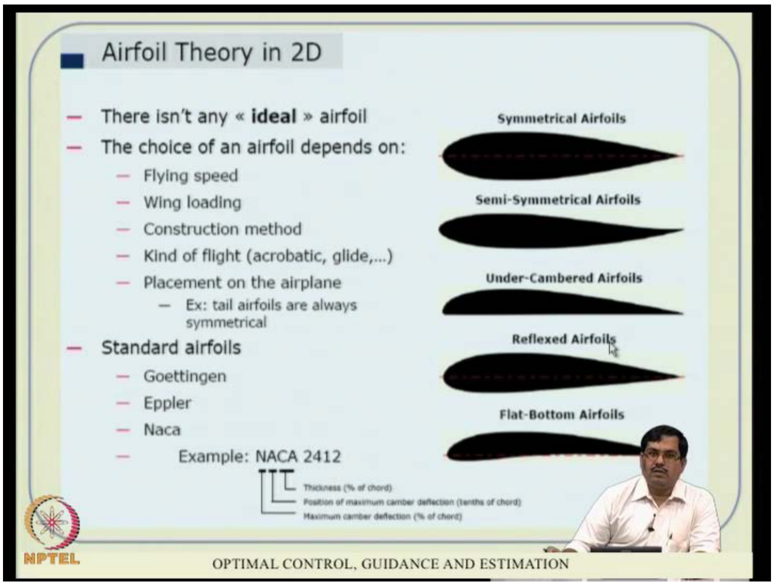

So, going to little bit in this airfoil theory, what, what aerodynamic people call, there will be various, suppose I take a wing and, and cut it through basically and vertically, then I will see some sections like this and this sections play a very, very good role in generating lift actually, and there are variety of ways of designing that and the different, different applications actually.

So, that means, the bottom line is, there is no ideal airfoil actually, airfoil depending on what application you are talking about, we will probably select a, that is best suitable for that application itself. So, choices are therefore, depends on flying speed, wing loading, construction method, what technology you have and kind of flight, what kind of flights we are talking about, placement of the, I mean, placement on the airplane, where you want to place the thing, things like that actually, got. There are varieties of studies, including Wright brother themselves studied a lot of things, but after that, there is a lot of studies about that and variety of wings are available around it actually.

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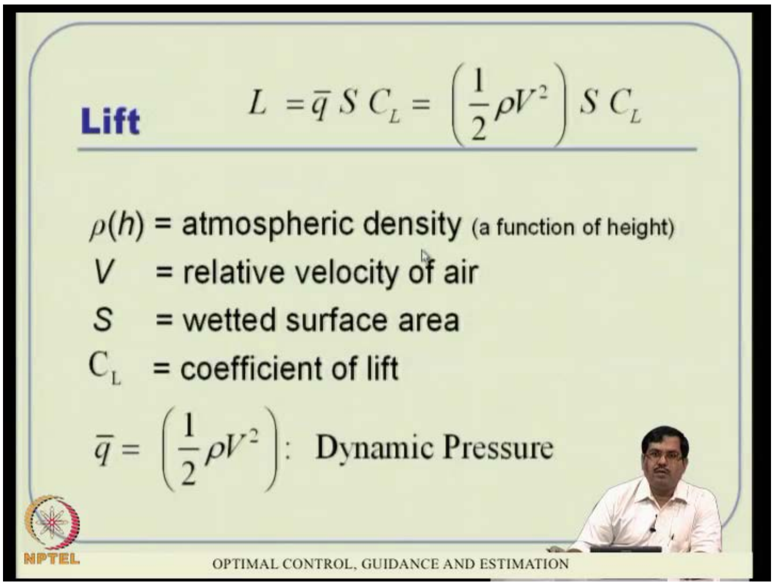

Now, coming to the mathematics part of it. What is, what is beauty for people like us in control system? This, this lift through expression, if you see, this is universally same, this is something given like this actually. This q bar is something called dynamic pressure and given by a half rho v square; S is something called wetted surface area of the wing, these are typically surface area is given to a particular, it is a number actually, given to us from aerodynamic people for a particular aircraft configuration; then, rho is obviously, atmospheric density and it is a function of height actually, we will see, that how it varies and then, there is a V square, which is relative velocity of the air actually, with respect to the vehicle.

So, this, this type of (( )) pressure, this is surface area and this is C L, which is lift coefficient, now no matter whatever aircraft we talk about, whatever design aircraft, whatever speed we talk about, it leads as a supersonic, subsonic, whatever flow done by anything, anything, any flying object, the good thing is the lift expression does not change actually. Expression is given like this, where all other effects are embedded into C L. That means, the model, that will, that will be given to, typically, will contain some expression on C L, depending on the application that we talk about and that may be given in the table of data. I think, like, that as, as as a function (( )) number, as a function of angle of attack, things like that and that can change entire, the overall formula will not change actually and that, that helps us quite a lot in control design and all that.

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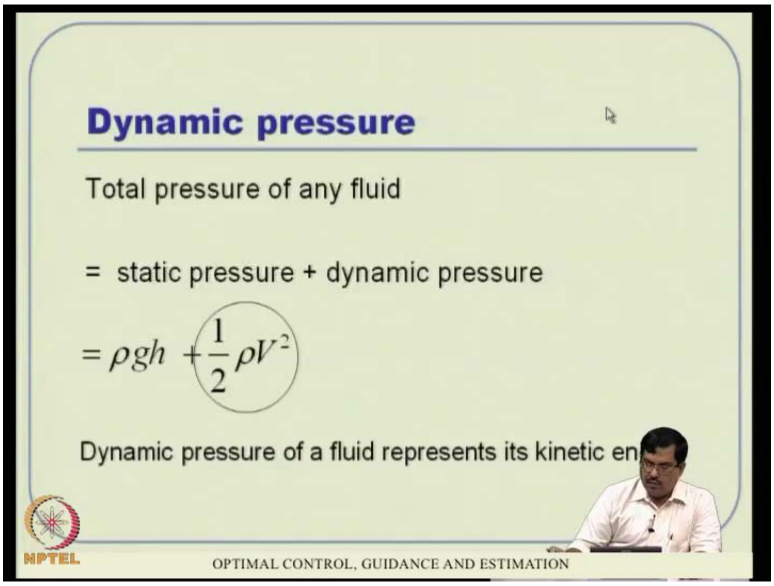

Now, coming to the dynamic pressure part of it and what we saw here is half of this dynamic pressure and this dynamic pressure is actually, you can visualize, the total pressure of the any fluid is partly from static pressure and partly from dynamic pressure, and the static pressure is rho g h (( )) potential energy sort of thing. And then, there is a dynamic pressure, which is essentially kinetic energy content actually. So, this is what plays a role in generating lift and drag essentially.

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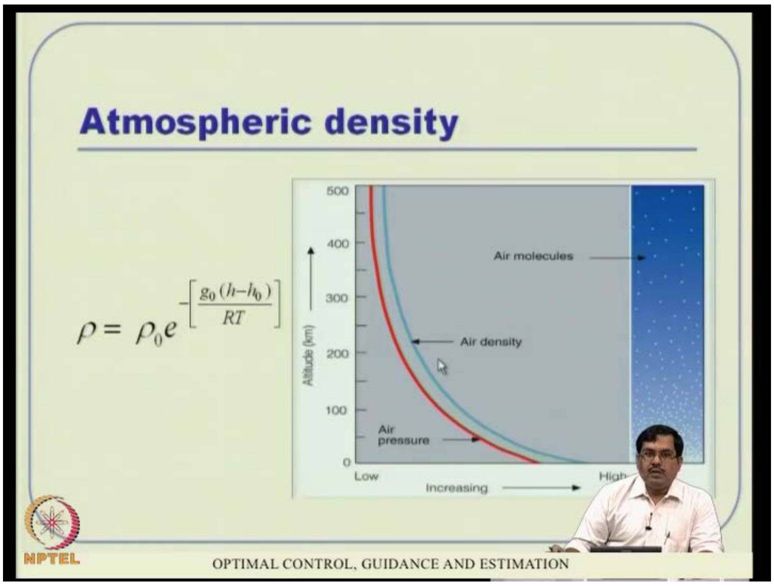

So, atmosphere density, if you, if you visualize, I mean, you see the, the, universally this remains true, by the way. So, if you see this at the distribution of air molecules, so on surface of earth they are very dense, as you go up and up and up and they are very sparse actually, and that is probably because of gravitational effect. On the surface of the earth that the gravity is very high, so you have lot of air molecules concentrated on the surface of the earth actually, here. Once it goes up and up and up, these, they are getting more and more sparse actually. So, essentially, what happens - the air density decreases exponentially.

So, if you, you can visualize this plot, something like increasing values being like this, the altitude becomes more and more, your height density starts decreasing, it actually, what you see here is altitude. So, if you go up and up and up, your density of air becomes low and low and low and that decrease actually happens in an exponential way; your atmosphere density is roughly given by this formula with a, with a negative components actually. So, what happens here is, the more height you are applying the dynamic pressure becomes more very low actually, I mean, lower and lower, ultimately it becomes very low and you will be not able to support actually, support your weight. So, that is why, it will be altitude sealing for a, for any given atmospheric flying objection and all that actually, anyway.

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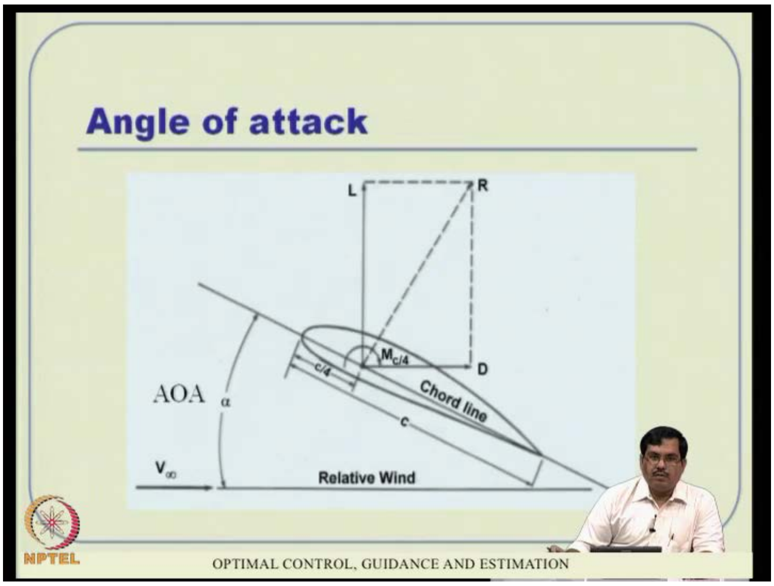

So, angle of attack formal definition, as I told, this free stream velocity and there is a mean chord line, if you see, take that angle then, that is, that is an angle, which is called angle of attack and that plays a very critical role in flow pattern distribution. As we saw that here, that is the angle of attack, flow, flow pattern entirely depends on that and that the angle plays a very important role in C L essentially. C L, what is CHCL here, that will be typically a function of alpha actually, and then, this is, this 1-4th of the chord line is something called centre of pressure actually, that this is where, if you take incremental pressure, incremental force and then summit of, then the movement becomes 0 out here actually. That means, the entire lift and drag gets generated out here, this is called centre of pressure basically.

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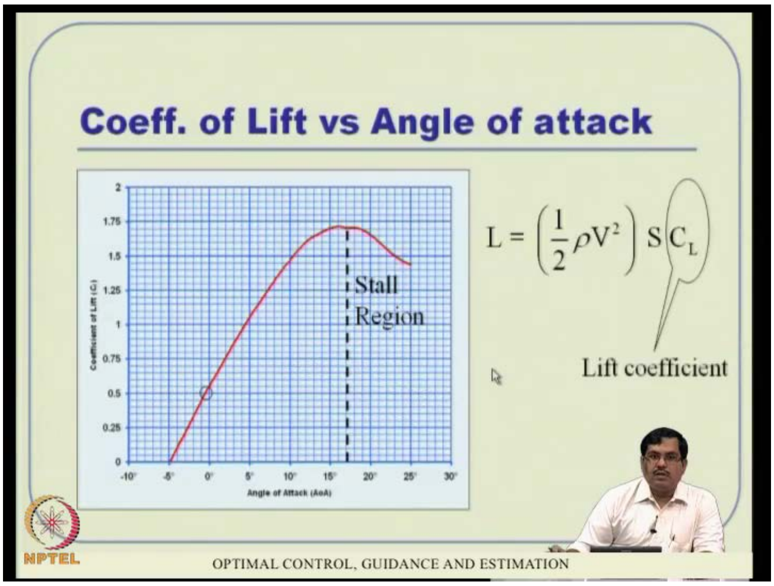

Now, coming to the gross behaviour of C L versus angle of attack, this is what actually happens. It starts like, fairly like a straight line, but at high region it goes, stabilizes and then, it decreases actually. This is something called stall angle of attack. Roughly, all the order, 17, 18, 20 degrees, depending on airfoil, actually what, what airfoil you are talking about. Also, remember, that when angle of attack is 0, you will have a positive lift actually; only when the angle of attack is some negative value, then only will have something like lift 0. So, any positive for 0 angle of attack, you still have some lift generation actually.

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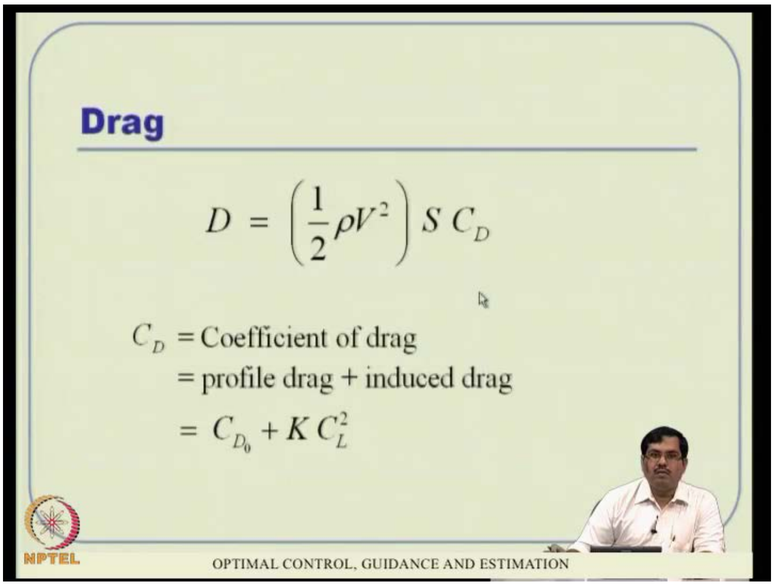

Now, coming to the drag part of it, the drag is also given by very close formula. Instead of C L, what you replace is C D, but also remember, that C D is roughly a function of like this, a function of CL in a, in a quadratic way. So, C D is, essentially, C D0 plus KCL square; that means, it actually varies in a quadratic manner always.

So, any amount of lift, that you generate, this additional keeps on building it actually and also remember, even if you do not generate any lift, even if C L is 0, still C D will be there and drag will be, will be, invariably there itself.

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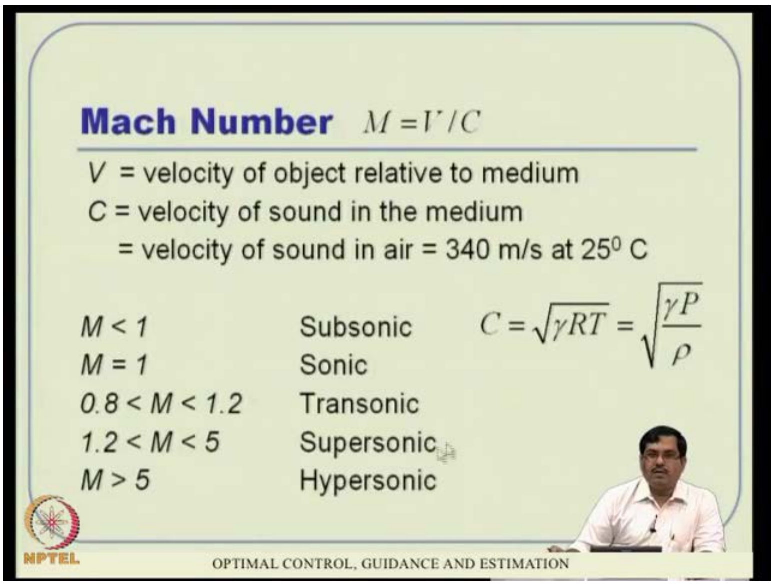

Now, there is another variety of resonance, that are, I mean, that are required in flight dynamic understanding and all, one of that is called as Mach number. And this non-dimensional flow quantity, this is essentially defined, velocity of the objective relative to the medium, whatever you are applying here in objective velocity divided by subsonic velocity. That means velocity of sound in the medium at that particular condition actually. So, velocity of sound is also function. I too remember, that velocity, I mean, it does not remain constant, but if you talk about 25 degree centigrade and things like that, the formula is given like this and it is largely a function of air temperature essentially, and also remember, temperature were also varies along with height actually, that variation and all are not given, it does not require very exponentially (( )), but it does varies with height, actually.

So, it remains like sea level at 25 degree centigrade room temperature, thing like that, that you can take this value as 340 meter per second actually. Now, what is the beauty of that, this particular number plays a heavy role in defining, what is called as subsonic speed or sonic speed or transonic, supersonic, hypersonic, things like that because the, the aerodynamic behavior is a strong function of this Mach number actually.

So, as long as you have subsonic speed, there will be not any (( )) generation, your aircraft velocity is lesser than speed of sound. Wherever, whereas M is supersonic thing and hypersonic thing, they will create as well actually, and unfortunately, it turns out, that during this transonic region, the aerodynamic phenomenon is never understood very well even now and hence, the modeling becomes very inaccurate actually here. Some of the reasons why this Mach number plays a heavy amount of a role and also, remember C L and C D are typically functions of Mach number actually.

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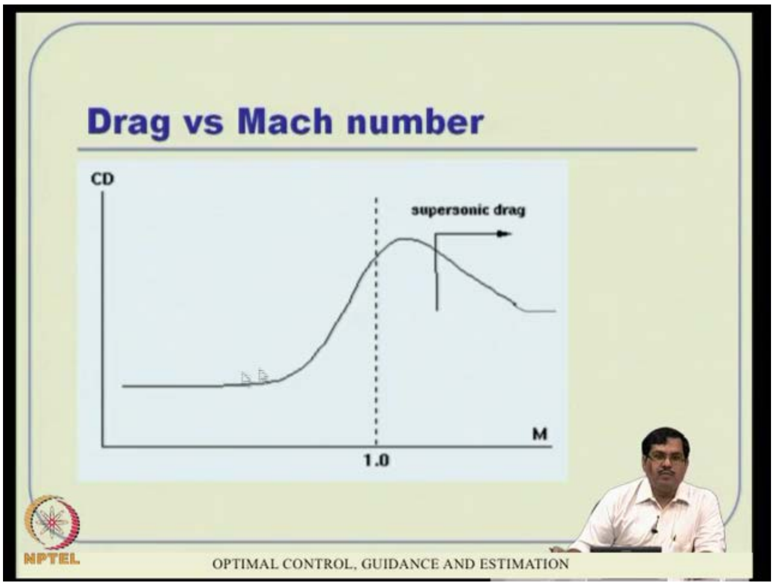

Now, C D, how, how it varies with Mach number is something like this in, in a subsonic region, there is a fairly constant value. Essentially, that you are talking is this, that CD 0 force on actually, not KCL square, then it starts building up very fast, then it will again decrease and it will stabilize after sometime, up to after high speed actually, like about Mach number 1.52. There are more, this, this will not change actually. Also, remember that this number, where you stabilize is higher than this number. That means, if you, if you really want to fly a supersonic speed, then your drag is going to be very high compared to subsonic thing; that is why, this commercial aircrafts are very successful in subsonic region. The moment you go to supersonic, the efficiency goes down, that is why this Concord aircraft was very expensive to fly actually, that was supersonic aircraft that is very unsuccessful commercially, basically.

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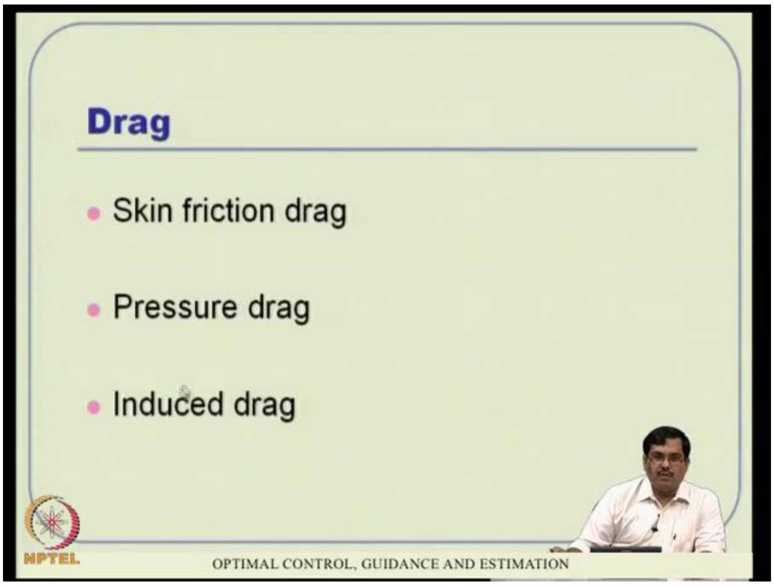

Now, coming to drag component, you can visualize, why these drag is coming. There is something like skin friction drag, pressure drag, induced drag, used various other components as well.

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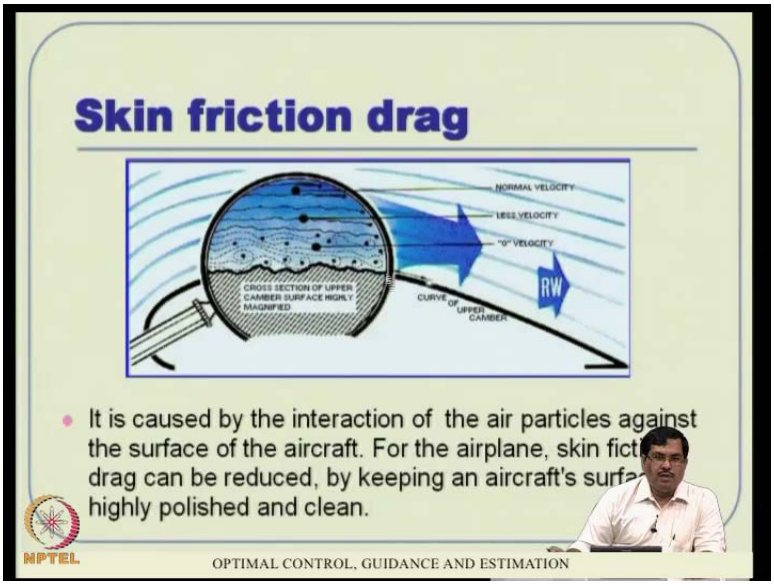

Let us see very quickly, skin friction drag is, essentially, because of surface area, non smoothness actually. So, if you take a very big microscope, you can see, what you see, what you feel like smooth surface is not really very smooth. It is as some, I mean, surface roughness because that there will be local circulations, something like, that they essentially a friction sort of behavior actually, that is called skin friction drag.

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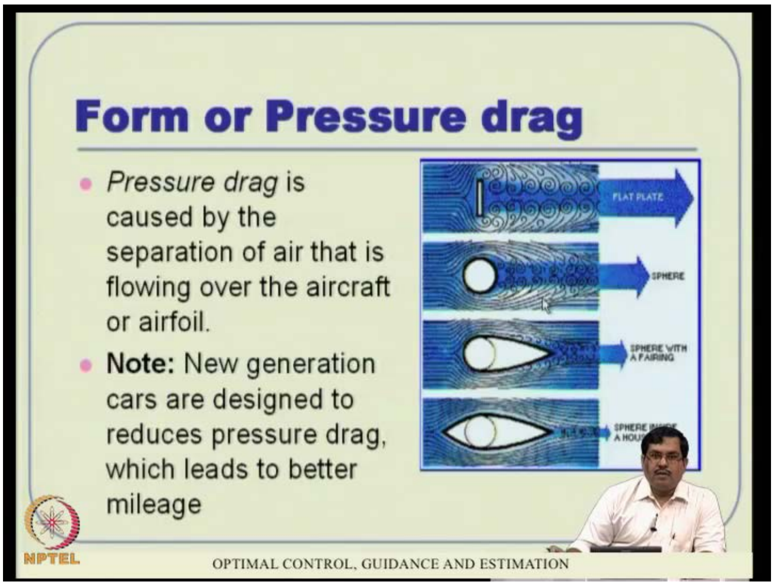

And now form pressure drag or something, it depends on the form of the (( )). Suppose, you take this vertical plate sort of thing, like that will, where you drag will be maximum because the entire flow pattern is completely (( )) after that. Then, if you take a perfectly spherical object sort of thing, things are slightly better than if you take this particular aspect, then they are still better and if you can optimize this particular design, then it can be very better, I mean, very good compared to all other thing actually. So, that, because of that reason, you see this new generation cars, the expensive cars, what comes after that, they also go for some sort of aerodynamic design because once you see the speed of the car is higher and higher, you essentially land up with, with this pressure drag itself actually. To minimize that, this typical shape of this cars will be somewhat like this, somewhat last (( )) sort of things, new, new cars.

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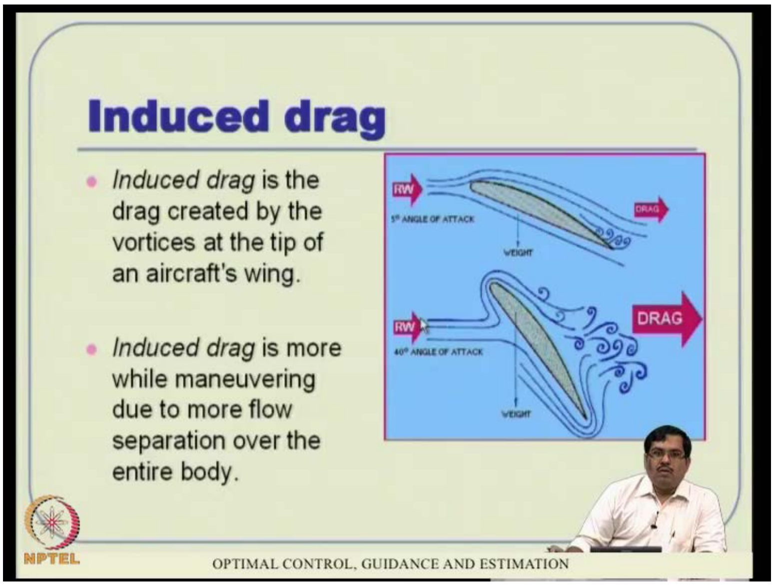

Now, induced drag, essentially we discussed about that as and I mean, this is primarily because of this flow, flow pattern (( )) because of this vertices, that is, that is gets created, I mean, afterwards actually, as that angle of attack is more, this flow of attack, vertex, vertex generation is more. So, you get induced drag more and more and is, this is also a function of a flow separation over the entire body, that happens more while maneuvering actually. See, if you are flying straightened level, then the aircraft structure is designed to be optimal in that mode actually, anything, any time, that it takes a turn, that are flow field is restarted. So, you will have more, more vertex generation and things like that. So, your induced drag will be more and more actually.

So, it is a strong function of your, what is called as, lateral resolution actually. So, the moment you generate a lateral resolution, a normal resolution either way, then it will have induced law component will go more actually.

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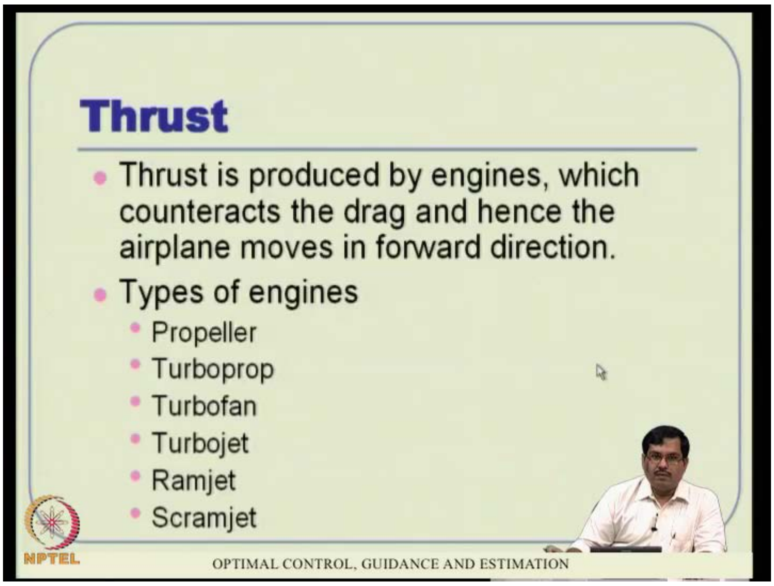

So, one of our control design methods, will see later in, I mean, if covered I will, will see later, that this missile guidance application particularly, I mean, I do not know, whether I will come up with one of our lecture somewhat, but one of the reasons, one of the objectives there is to minimize the induced drag through an optimal latex generation actually. That is the one of the condition that will lead to, and essentially, this is what is called as P N guidance, which is very popular in missile guidance, that, that implicitly it does that anyway and so those things are there actually.

Now, coming to the thrust force, see you remember, there are, we talked about weight, lift, weight versus lift and drag versus thrust actually. So, this thrust generation happens through variety of ways and you can essentially use an engine to do that and it can happen through a propeller, through turboprop, turbofan, turbojet, ramjet, scramjet and a variety of thing. It is a field by itself and we are not going to discuss too much on that, what we are, what we really need is a thrust generation mechanism in, in, in control system design, as well as, it will limit extend. This, this thrust generation mechanism, mechanism, will also give us some sort of control force actually. We can manipulate the thrust required, the magnitude as well as direction to a limited extent, this is a thrust vectoring, what we call (( )). So, these 2 are, these are possible, I mean, available. However, varieties of ways of generating thrust, actually, let us very quickly see that.

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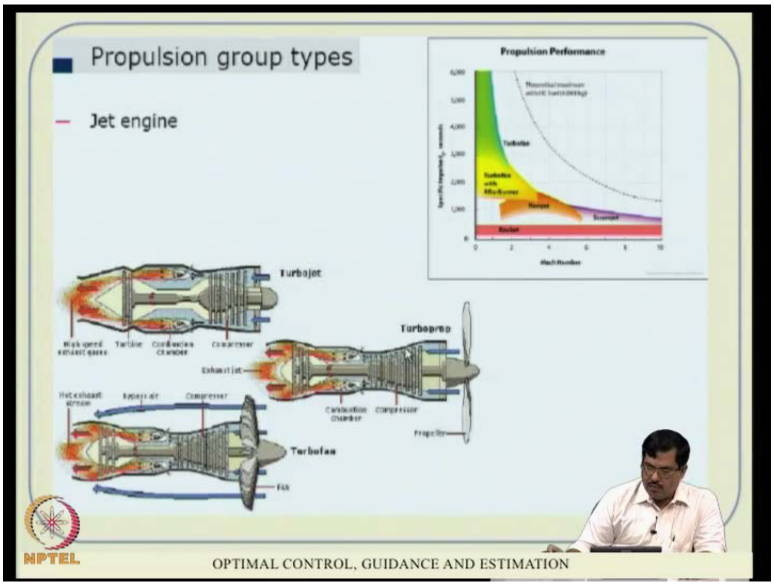

So, jet engines can be classified into like turbo jet, turbo flow, turbo fans, and things like that and this is roughly the behavior what we expect actually, I do not, whether this, this slide is not very clear. So, what is plotted out here is Mach number versus specific impulse ISP and this ISP, this is, by definition something like thrust by mass flow rate actually.

So, how much mass flow is there, how much fuel is essentially to generate that much amount of the thrust actually, that is, that kind of an idea there. So, if our ISP is higher and higher, your engine is operating in a very good efficient manner actually, but unfortunately, what happens is, if you really want to fly with Mach number higher and higher, that is no more possible actually. So, if you, this, this class of vehicles actually, what will operate on turbo fans sort of idea, they operate on very low speed, actually, Mach number less than 1. So, we are, efficient ISP can be kind of a, high actually there, here, this region.

And on the other hand, this is what is it, rocket engine, rotating engines are very inefficient, there ISP is very low. However, you can fly with, with whatever Mach number you want, Mach number 9, 10, whatever you want. So, we can go through whatever degree of speed you want, so that there will be something in between. There are some concepts of something called ramjet, scramjet, thing like that, this is because of something called ramming effect, that is the name ramjet comes, then the supersonic combustion, ramjet is ramjet and thing like that actually.

So, there are essentially, I mean, this modern aircrafts essentially work on either turbo fan or turbo fan with (( )) things, actually or sometime they, they work with turbo prop as well and where some applications, we will see actually.

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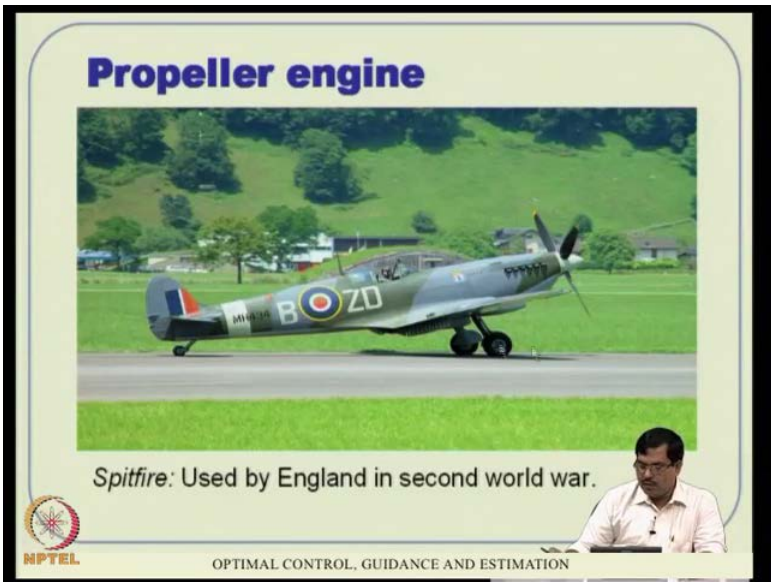

The propeller design, the propeller engines are essentially old ideas and they are, one example is this aircraft because we, used by England in 2nd world war actually, it, it was in practice actually, it was operation successful.

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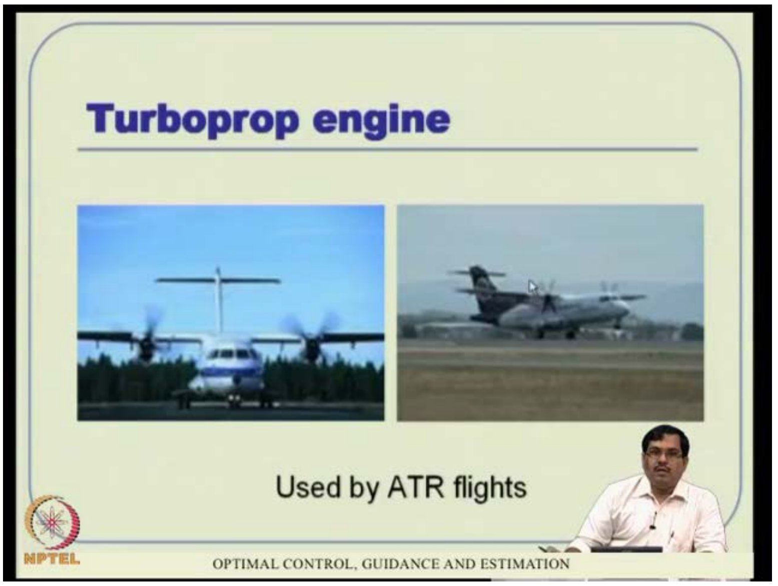

Turboprop engines, you see, now there are many ATR flights, that we takes a short, short duration flights with less, lesser number of passengers and all, they are efficient in that region, they essentially operate in, in, in that region actually, like this turboprop variety sort of thing, actually. So, ATR flights do use turboprops actually, this is, I think, many of you have seen this in airports and probably many of you have flown also actually.

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Turbo fan engines are typically used in big commercial aircrafts in, in turbo fan engines, remember, are lesser very less noisy actually because the entire rotational mechanism, if you see, they also go inside the casing, basically, so that they are both efficient as well as they are less noisy actually. So, that is, that is where you see these are used in commercial aircrafts, big aircrafts basically for example, (( )).

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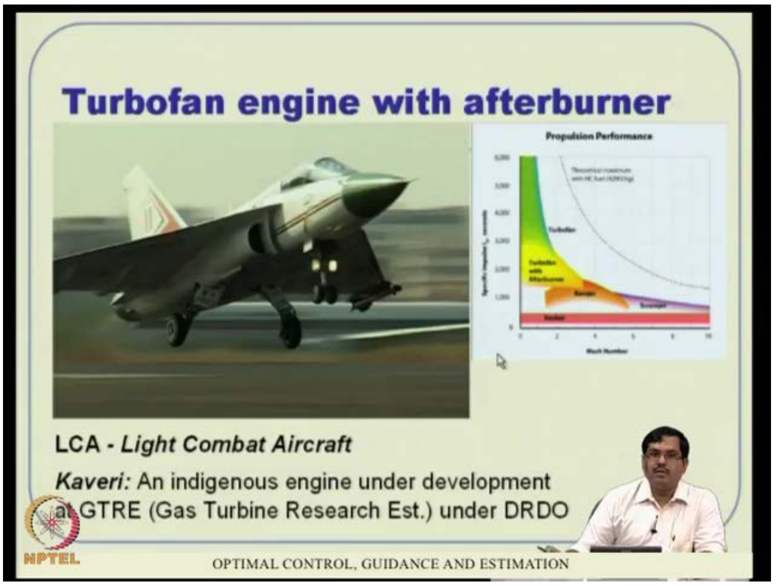

Turbo fan with after burner, afterburner essentially remember, if you see, go back to this flow chat turbo, turbofan with afterburner is this region actually, whereas, only with turbofan is that region. So, if you really use afterburner, you can push that velocity to Mach number supersonic region actually. So, you, you will, your ISP will be lower, that means, your engine efficiency will come down, but your vehicle speed will be higher actually. That is, where your (( )), for example, we will see, we will use that actually, this is a light combat aircraft wing design actually.

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Ramjet engines are used in, essentially, they are used in missiles because ramjet engine operates somewhere here, very low specific basically, so, that, that attempts are being made to make a commercially successful as well, but because of this they are typically a concern actually.

So, they are supersonic combustion, I mean, some, something called, ram, ramming effect basically. When your vehicle velocity is more than Mach number 1 here in supersonic region, you really do not need too much of this, this complex mechanism, what you see here, they will be like, compressor is not needed, turbine is not needed like that actually. So, and then, but the software management becomes a critical issue there actually. So, your software management inside goes inside the engine and you really do not, I mean, have that much liberty here to manipulate as you want actually. So, there, there are critical technologies out here actually.

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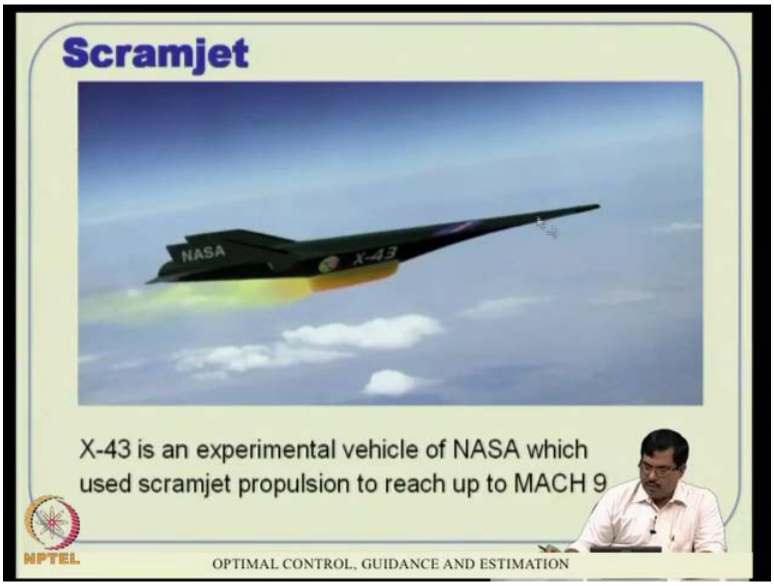

And then, still further technology boundaries towards that, I mean, this is not successful yet. However, people have only this, only test flown and demonstrated for short durations, that you can even go up to Mach number, actually, 9 actually, that is being demonstrated by NASA in that X43 flight actually.

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This is a missile operating, this real missile operated, I mean, developed jointly by India and Russia, it is, it has been test flown and being inducted actually. So, this is variety of missile, these are available, which will really operate on Ramjet principal actually, this is just one of the, that actually.

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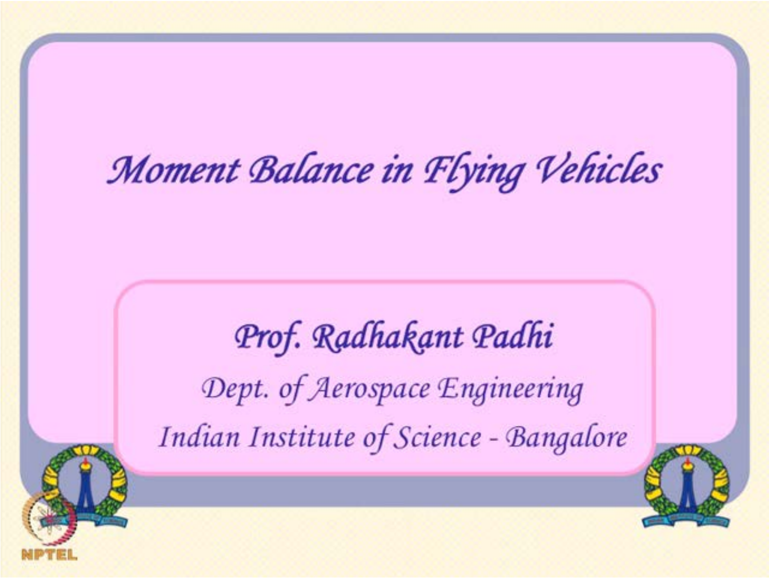

Now, coming, these are also called, like force balance we studied, now let us see very quickly, what is moment balance as well, that is, moment is also critical in, in, in a flying object and essentially, moment is the one, which gives us controlling the afibility of a vehicle, not force actually, force gives us propulsion characteristics and all that, but by changing the moment, changing the rotational VIPR, we will be able to control the vehicle actually, that is where we see that.

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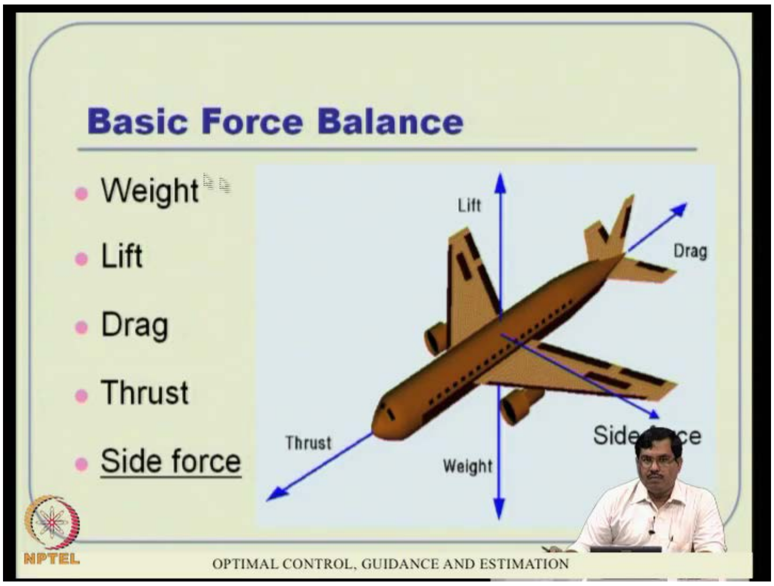

Now, just a quick review, what we saw their force balance is weight, lift, drag and thrust. Also, remember, that there will be a side force component actually, that we typically neglected that, assuming that to be 0 there. So, this, a drag is not perfectly received, thrust is normally aligned perfectly like to the nose sort of thing, that is by design, but drag, you do not have a choice typically, drag is actually opposing to the velocity vector and velocity vector all the time need not be aligned to the vehicle nose actually. It can, that can go somewhere inclined, once it happens that way, that is, the velocity vector, sort of thing, let us say, the velocity vector somewhere, something like this, this is velocity, then there will be an opposing force, which is there and that you can resolve into 2 components, that, what we, what we have seen is drag before and then, there will be a side force, which will also come there typically. There is no mechanism to cancel the side force actually. So, in general, we do not want side force generation, that is what is called as like turn coordination actually, coordinated turn and all that, anyway.

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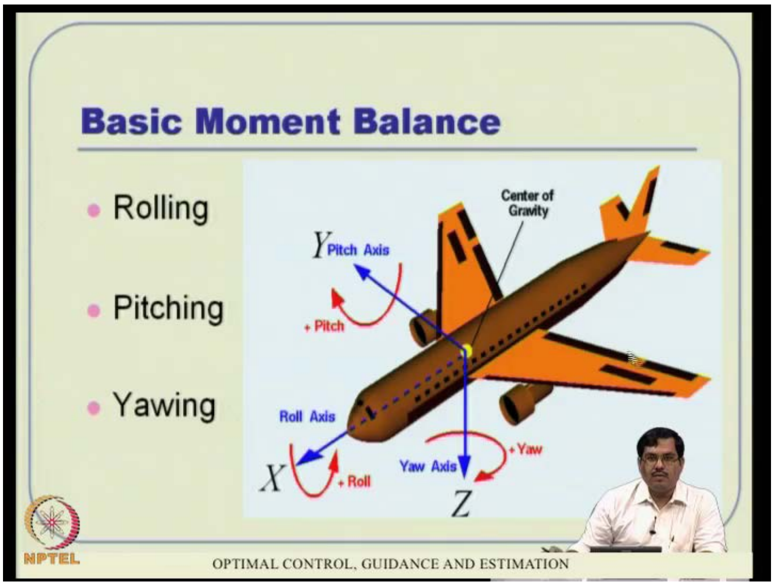

So, the basic the moment balance is, essentially 3 moments are there, one is rolling moment, another is pitching and another is yawing essentially. This, this is something called body axis actually, you can visualize an axis frame setting on the central gravity of the vehicle, where x axis is pointing to the nose, y axis is to the, what is called as, star board, right side of the, thing, wing and then, there is like, the vertically down is something called z axis actually.

So, any rotation, if you can grave that axis, so that way, pointing to the right or whatever, this is the, this, this side, this side is your, like thumb should point out, then your other fingers will point in that direction actually, sorry, your thumb is in that direction, this will become in that direction actually, this is the positive rolling moment. Similarly, if you grave this axis, your thumb pointing towards that, then the other fingers, wherever the point, that is called pitching actually, we will see that one by one here. But we will see, that first is roll, rolling is about a positive x axis, pitch is about positive y axis and yaw is about positive z axis actually. So, roll, pitch and yaw, those are very critical in control system region applications as well, I mean, we see that actually.

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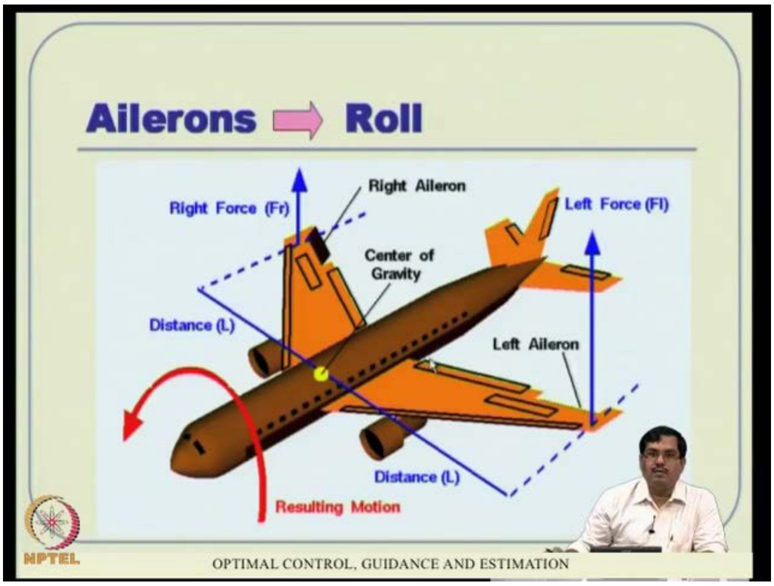

So, what is, how do you create a roll motion, rolling motion? Suppose, really want to cancel the, the unwanted roll or you want to create a wanted rolling thing, as I want to take a term, then you have to create a roll, as well, rolling and we, having typically coupled actually, if you see this, this roll and yaw are typically strongly coupled whereas, pitch will be slight decoupled from these 2 normally.

In general, all 3 are coupled, but these 2 as strongly coupled even in a linear set of, we cannot neglect the decoupling part of it, whereas this part is fairly decoupled from these 2 actually. Now, how do you, how you create a rolling motion is essentially done through, create a, creation of differential force through this cut-outs actually, what is called, what are called as ailerons actually.

So, there is a cut-out here on the right side of the wings and there is cut-out here in the left side of the wing. Suppose, you, left side you turn it down, then your angle of attack essentially goes a little bit higher in this side, so that means, your lift C L becomes more, so you get a larger lift force here, whereas you get, you deflect in other side, you get a lesser lift force out here because the angle of attack, the effective angle of attack, you are reducing by deflecting it up actually; by deflecting it down, you are increasing the angle of attack, so the left force becomes more. So, what is happening? The larger force here and a smaller force here, so that means, there is a differential force, which is not, turns is, it is far away from.

So, it will create some sort of a move, some sort of moment here actually, about C G. So, that effect you are seeing, so the moment you try to reflect, like up and down, that, that will roll like that actually, this aircraft, this effect is called rolling effect.

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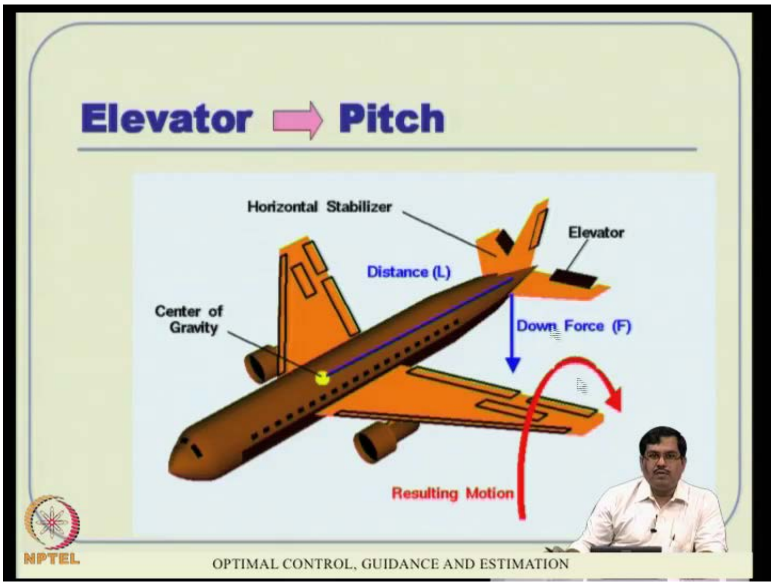

Now, similarly, if you see the, the pitching, how do you create a pitching action is largely though this, this elevators. So, they are deflected symmetrically actually, either both up or both down. Once they are both up, then you have essentially, there is a downwards force, make, they are differential downward force, remember that they need not be the complete downward force, aircraft need not come, need not go down, but there is a slight downwards force here, but it is far away from C G.

Remember, this length is very high, so you get a large moment, which gets generated out here actually. So, then, that will, that will create some sort of an upward moment actually, the pitching action basically, that is what will happen while deflecting the elevators.

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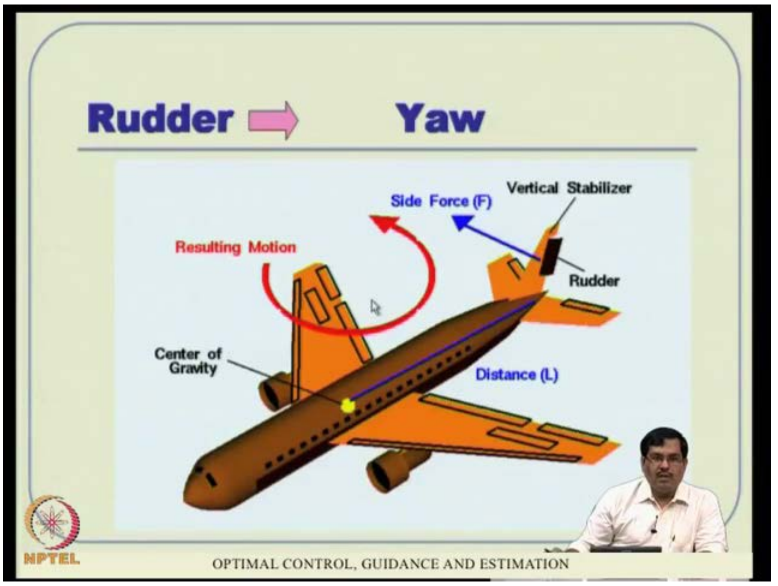

And similarly, the, the yawing action is typically controlled by rudder, rudder if you generate left or right. So, there will be a side force generation essentially. So, that side force will create a resulting motion actually in, in a yawing sense. By the way, this rudder is also used to nullify this, this, this side force that I talked actually. If you really want to nullify this side force, then the rudder is the mechanism to do that, but it is not very effective that way, it is very effective in generating a moment because of the momentum, but generation of force is not very much capable, none of the control surfaces are very capable of generating heavy amount of force, they, they generate a small amount of force, but because the moment is, is long, the moment creation becomes strong actually. So, this is what happens through rudder moment actually.

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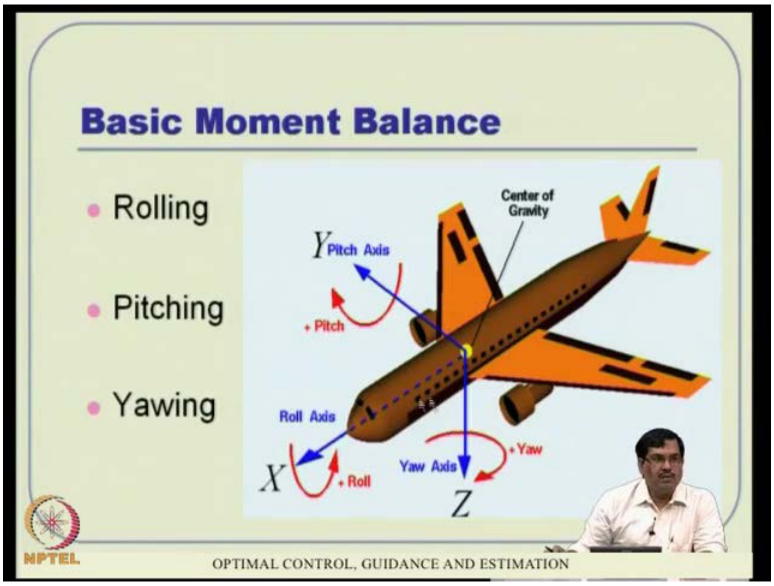

Now, coming to that, this, this, this motions, what you see, neat, neatly, these are actually coupled motions, these are not decoupled motion. Let us see that one, one at a time again, you have, you have these 3 axis x, y and z, any moment, any, any, these moment, rolling action about these is called rolling actually, angular, angular motion about this x axis is called rolling action, then angular moment, motion, angular moment along y axis is called pitching action and angular moment along z axis is called yawing action. And for controlling the roll, we have ailerons here for controlling the pitch, you have elevators right there for controlling yawing, you have rudders, which is right here.

Now, there are additional things, as you know, this are flaps and this are, this are spillers and this are slats, and all that, they are typically used during takeoff and landing essentially, all other time they will not be used. So, they are momentarily used to either to, for example, if you, spoiler, you just you cannot make it down, it is on the top surface of the wing, top surface of the wing. So, you can only take it up, where that is, once you do that, what happens is, there is a heavy on to drag created actually and these are done, not difference, they are done symmetrically, you cannot do differentially, anyway, differentially you can do, provided you deflect this one 2 degree and that one 5 degree, I mean, that is the difference actually, but typically, both have to go up actually, they, one cannot go down and one cannot go up actually, that way.

So, once you take both, both up and equal angle, then, then what happens, this, this moment, that you generate is down track to by that, that moment essentially, moment generation will not be there, but what will happen is there will be a force generation. There is a traditional drag will create actually, that is typically used by landing the aircraft. Once you, those of you have flown the aircraft and seen landing carefully outside the wing, you will see, that during landing, after landing, after touchdown the, the, suddenly these guys go up to create a heavy amount of drag, it is essentially like a braking mechanism actually.

This slats, what you see there, they are deflected downwards typically to have more flow attachment, so that your lift becomes more. So, that happens during, essentially, takeoff and landing actually, lift becomes more, drag also becomes more in that way, either way, whatever you want, while taking off want lift more while climbing down, while touching you want drag more actually, so that flaps are also deflected vertically down.

So, they have, I mean, these are primary control surfaces, there are many other secondary control surfaces as well, we are not going to talk too much on that. For example, this elevator cut-out, what you see here, what you saw here, there will be a further cut-out somewhere here, which is (( )) actually. So, if you really want to fly on a condition, then not only this has to go down, but that little portion, end of that particular surface will go up actually. So, these are variety of considerations you will see in a flight mechanics course, this is not a flight mechanics course, this we will not talk so much detail about that, but many, many other considerations do come into picture.

And there are all sorts of forces and moments that you see, they are all coupled actually. That means whatever forces you see here, like they are not separated by from each other at all actually. So, that is a, that is how its, its non-linear coupled equation and there are 3 axis, you remember, that on 3 axis, you will get, like 3 forces and 3 moments and all of these forces and moments are governed by Newton's 2nd law actually, and each Newton's 2nd law is f equal to m k double dot, remember that.

So, once you have double dot formulation essentially, you can convert that into state space form in single dots into 2 differential equations. So, what essentially you have is 12 differential equations, three, 3 axis, 3 forces and 3 moments, 6 actually, 6 each are 2nd order equations; that means, you will get 6 into 2, 12 equations in total actually. So, those 12 equations will be coupled with each other and those, that are, the equation, I mean, that set of equations are the one, that we are going to use in a non-linear control design for a, for flying objects in general and aircrafts in particular actually.

We will see those details little later actually and there is variety of other things, so suppose, suppose, you really do not care about so much of details. Then, something called point mass equations are available you care about. Let us say, missile guidance of long duration really do not need to care as far as trajectory optimization or as far as guidance problems is concerned, really do not care too much about how my aircraft or how my missile is, kind of, what is the attitude of my missile, what is, what angle it makes actually, as long as I go close to the target, I am, so as far as guidance problems are concerned, that typically, you will use point mass equations not so much detail actually, but when you come to control design in a good way, you really have to use, what is called as six doff equation, that is, that is what I just talked about. 3 axis are there and 3 forces and 3 moments and each are of 2nd order equation that essentially consists, so what constitutes a 6 degree of freedom equation of motion actually. That is what is, will be used for control designing in general actually, alright.

So, all these things, we just saw that one more time. Let us say, this is aileron for rolling control, that is what it will happen, this are, remember these are getting deflected, the, the dark ones, the solid ones actually, that is the ailerons and this is, this is elevator. So, these are the ones, which are used, that is, how it will be used and like that and this is a rudder thing, which will deflect if you deflect left and right, that is what will happen, there is called yawing motion actually.

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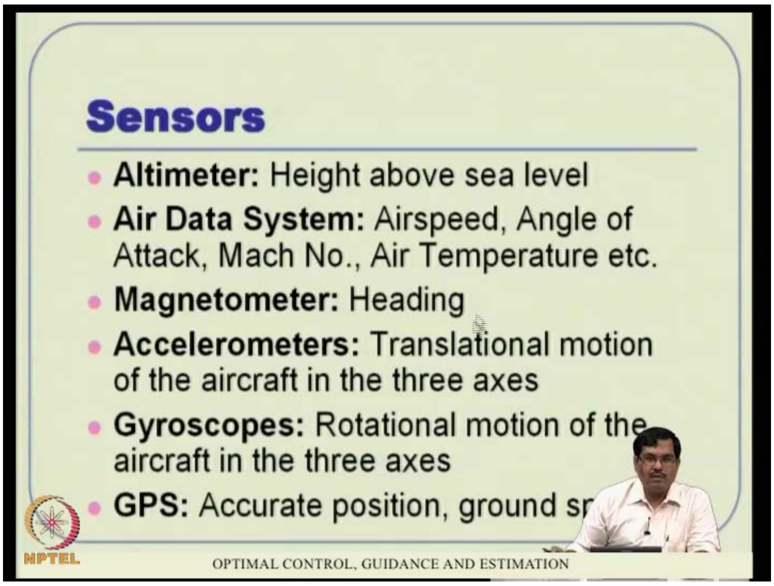

Now, coming to the sensors, also remember, that it is when you talk about automatic control of aircraft, it is really heavy amount of sensors to what it, what goes on in the vehicle actually and it is a very sensoric system, rather the modern day aircrafts or in a sense, whatever we talk about in vehicle missile, even satellite it is all these are very highly sensoric actually, and in the sense, you can get the same information using multiple sensors as well, that gives us sensor (( )), that one fails, other is still there. It also gives us data fusion capability, that means, if you take one measurement of the one sensor and the same measurement using 3 or 4 sensors, I can fuse it in a good weight to get very good accurate information actually. So, all these are, are, are used actually.

Now, come, what are the typical sensors that go in an aircraft? You can think of 1st stage and altimeter, we really need to know what height your are flying, then there is an air data system, which, which gives a host of information, like air speed, angle of attack, Mach number, air temperature, etcetera, etcetera, many things will come from there.

Then, there is a magnetometer, sometimes used for heading things. Remember, if you put a compass sort of thing, it will always point to the north actually. So, if you put a very good compass, let us say, easy or something, it will always point to north, so you will know, which heading you are all going actually, what is your, what is the direction of your vehicle, that is a magnetometer.

And all these have their own limitations and, and advantages actually. So, depending on what application we talk about, it should use, use, that sensor information in, in a clever way rather. And what is invariably there in, in modern day flight of the, I mean, flight vehicles is something called INS system, industrial navigation system, and essentially, that consists of, and the airoscopes, these are invariably there. Accelerometers are essentially, they measure translational motion of the aircraft in the 3 axis, they will, motion these, like translational speed, translation isolation, things like that, they will measure that. That means, along, along x, y, z axis, what we saw here along x, y, z, there will be a velocity component, that, those are called UW and things like that, those, those quantities will be measured through as accelerometers.

And then, the rolling motion, the angular motions and all, they will be measured by this, this gyroscopes. So, the rotational motion of the aircraft in 3 axis are measured by gyroscopes typically, then there is another set of sensor, which equal GPS, global positioning system, they essentially operate through satellite information and all that, there are 24 satellites, they often and you acquire some forable satellites at any point of time around blow, that is available by the way, and then, out of that you collect the information of the satellites, and at which point of time they emitted that signal and using those information, you calculate your own position actually in a very good way.

It turns out to be highly accurate system, however it is subjected to signal availability from this, from the order, I mean, from the satellites and essentially, that is controlled by US. So, there are also, like parallel systems available, like GPS, where, then call something, are still getting developed like a thing, like that actually. They are same concepts, they operate on 2 frequency band also, one is available throughout the world, that is, is civilian frequency band and there is also a military operation band, which that normally do not give it to other countries unless it is a very highly friendly country, probably it is available only to Israel other than US, may be other countries is not available actually.

But it is really accurate system, it, not only it measures position, it can also measure ground speed as well and thing like that, this is not an exact, there are other sensors available as well actually. Sometime, for example, star sensors, they are available for, for measurement, but they are, they can be used x atmospheric, that means, for satellite application, they can be used actually. So, that itself is a technology bytes, I mean, in a, in a used way basically, and gyroscope, they can call mechanical gyroscope, there are fiber gyroscope, there are laser gyroscope and many things actually like that. Accelerometers, similar way, there are and there are for UAV applications, they are typically level, it is a micro electro-mechanical system, they are manufactured, that for actually they are low cost, but not that accurate system actually.

So, this is, so what I mean is, as lot of information will keep coming through a variety of sensors, which will be essentially process by in your, by one more computer, to give a control command essentially.

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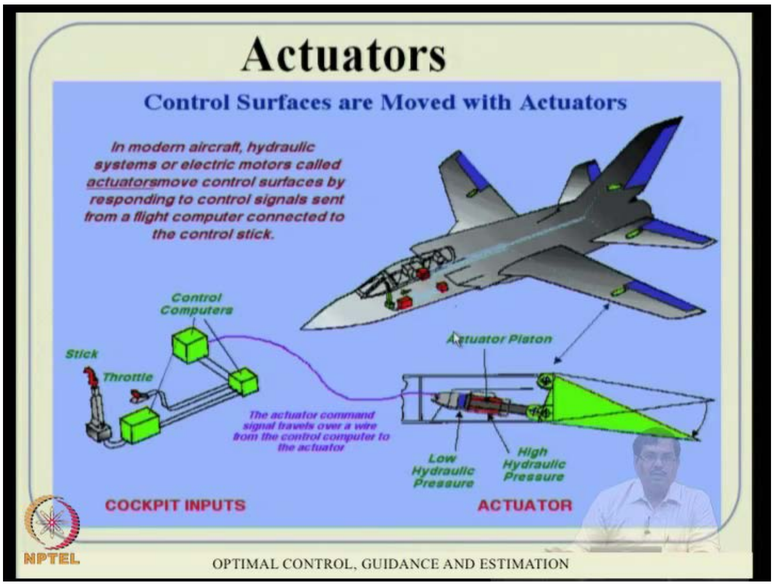

So, that is ultimately executed through actuators, actuators will be situated, now modern day aircraft actuators are situated right there, where you really need that and the command, as everything goes through all sort of computation through, through a flight computer and essentially, the signal is transmitted through a wire to this, this actuator system actually actuates the system, it deflects that, that aileron, for example.

So, what is the required amount of computation, that how much degree, how much deflection you need to give, that essentially compute using your flight dynamics, using your control system technology, everything. Now, ultimately, you will give a command to this actuator, that actuator takes the command electronically through wire and then executes it through some sort of, like a motor and all that actually, either it is a hydraulic system or it is an, electric, electrical system as well actually. This, this is because all these things happens through wire, not through extensive mechanical mechanism, they are also called fly why wire control system. Everything, information is taken through variety of sensors, they are processed through, either through low kalman filter, filtering whatever you want to do. Then, those processed information are used in flight control computer, I mean, control design algorithms ultimately, this, the output of the algorithm is passed back to this actuator and essentially that is executed there.

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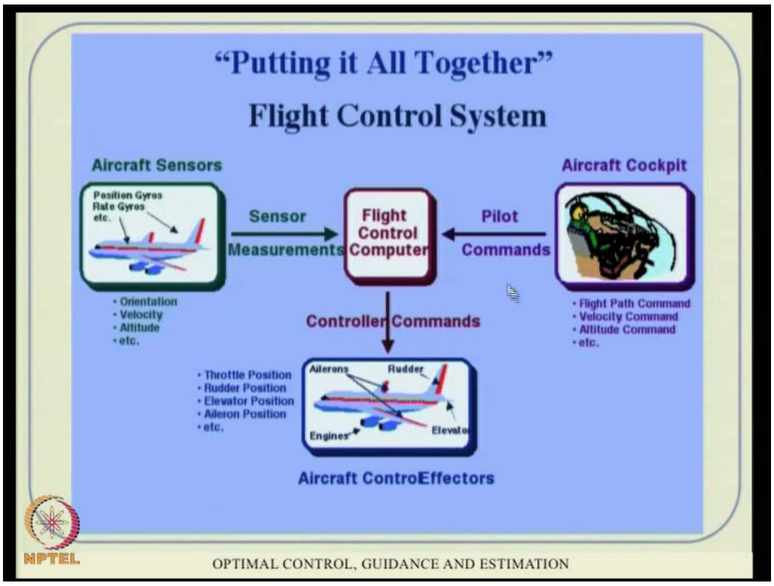

So, in a nutshell putting it altogether, there is a flight aircraft sensors, which will sense the measurements and then pilot command also pilot will see outside and all that, that also you can, that a huge amount of sensor, that goes through pilot organs basically, like I, sort of things then, he gives a command essentially, that, that also counts to the control computer. It goes through a variety of computation, then it gives a control command, which is essentially executed there.

So, the entire control mechanism essentially deals with this flight control computer. What we will deal here? We will talk about algorithm development essentially using here the various variety of models, the point mass of (( )), of whatever, how do you generate a good control algorithm, which will essentially be given to the controller actuator, essentially that is our entire objective here in this particular course actually, this where I will stop for this class.

Thanks a lot.