Advanced Control System Design

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Lecture No. # 06
Basic Principles of Atmospheric Flight Mechanics

All right, last few lectures we have been reviewing the classical control systems and we saw many aspects of that including frequency response. So, some of these I mean these are the references for that, if you want to study further details. The first one is my first choice of course, I taken many many examples from there. That should be comfortable for you to read. The second one is also a good book, but it primarily, I like these frequency response concepts as well as some concepts of modern control theory like, straight phase systems and all that actually state phase representation. We will study that later.

The third one is we will see lot of examples; it is a Schaum's outline series. So, if you really want to practice a lot of examples, you get comfortable about (( )) I mean the topics and all you can see that. The fourth and fifth are primarily we will see lot of applications of this theory what you study here in flight control applications, aerospace control especially to aircraft control structure. The last one is about engineering mathematics, so some of the mathematical concepts if you want further references, then you can probably see that actually.

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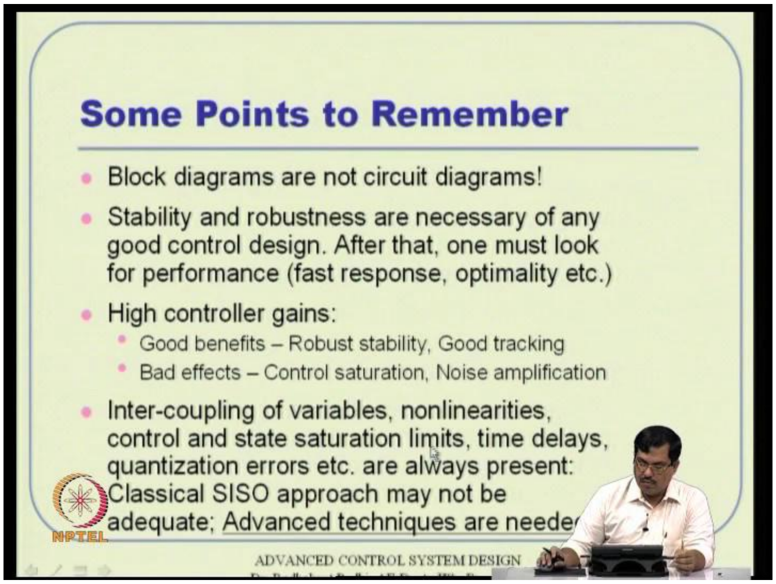

Before you move on the some points you remember, we discuss that at length in the first class itself, we are still to recapitulate. First thing first thing first, the block diagrams are not circuit diagram. That means, the things that we study here are not necessarily confine only to electrical engineering. They are very much confining to mechanical, aerospace something like that. Circuit I mean, circuit diagrams contain electrical circuits for say, but block diagram is a diagram representation of ideas specifically what we have and things like that.

Then, remember that stability and robustness are necessity for any good control design. We cannot get away from there; we have to talk about that. However, after that one must look at other performance conditions as well. That is like first response, optimality etcetera. Then, also remember that invariably we do not select a high control gain, because there are good and bad things. Good thing is robust stability and good tracking behavior, however bad effects are control saturation and noise amplification.

So, while you tune your gains, you should remember these things, so that you can select some gains judiciously actually. Having said all that, also remember that inter-coupling of variables, nonlinearities, control and state saturation limits, time delays, quantization errors etcetera. Many many practical aspects will always be there. And hence classical single input, single output approach may not be adequate.

That is why we are there in this course to study advance control techniques actually. Those are the necessary for doing that, I though before move on I should remember these things invariably. All right that is what this end of this last class and we will move on further too. This particular lecture we talk about some basic introduction of atmosphere, atmospheric flight mechanics. There is nothing to do with too much of extensive detail, I mean this is a course by itself.

I will talk about many many details of that, but I assume that many people who study this course may not be knew 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 equation involve in that and how to manipulate that using control system theory. That connection we learn later, but these particular classes we will just see some basic principles of flight mechanics.

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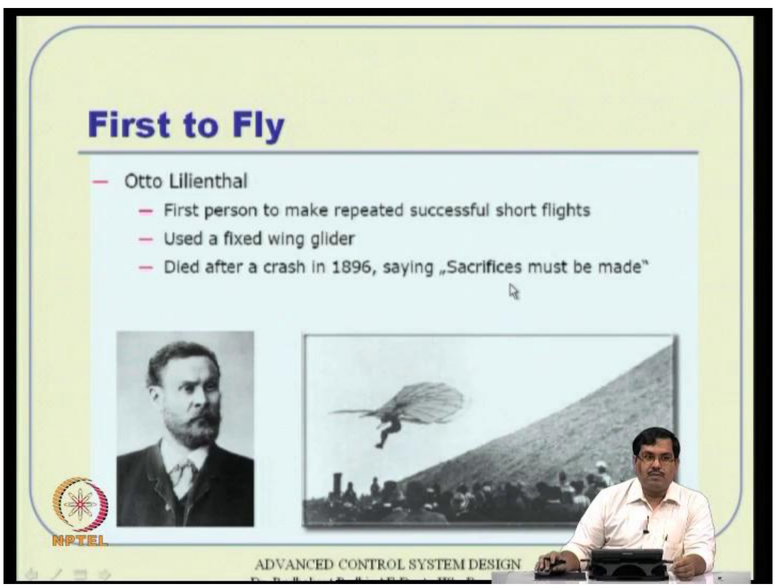

First of all, there are various aircraft designs. If you see, first to fly probably goes to this particular gentleman here. His name is Otto Lilienthal someone and he actually the first person to make repeated successful short flights actually. So, it is kind of mimicking the bird sort of thing attempt to that.

And essentially he used a fixed wing glider, and then obviously died at in a crash in 1896. And purposefully, he knew that the risk involve and he kept on saying that saying that sacrifices must be made. And that is the great sacrifice in fact actually. So, he is the first person to attempt flying like a bird.

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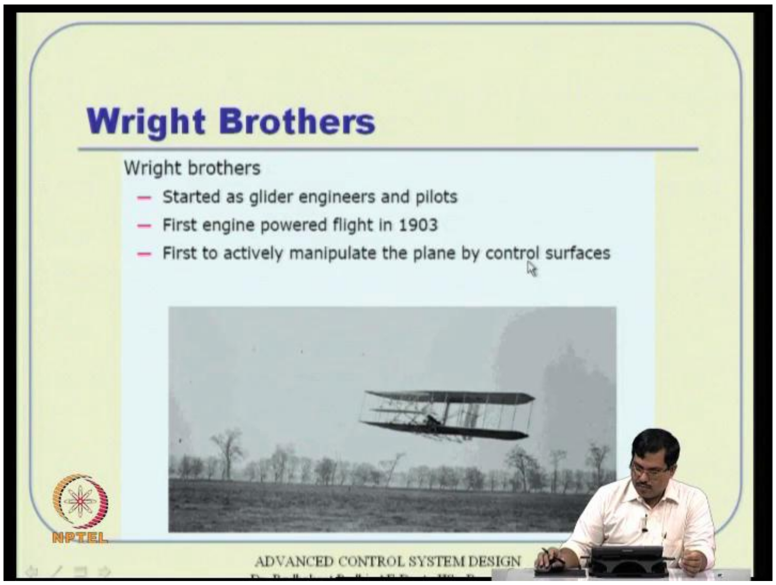

Then, the obviously we all know that the next big credit goes to Wright brothers. And they started as glider engineers, and later on pilots as well. They did lot of internal testing followed by optimization and things like that of the wind structure and things like that. However the most credit for this Wright brother's successful flight goes to the control surface. They are the first person to realize that uncontrolled flights are simply not possible. You need to have a control system for successful flight.

So, that is the reason probably why they were successful, where others were not that successful. It is also the first engine powered flight in 1903, just about a hundred year's back hundred hundred five, six years back. So, within that there tremendous improvement in this field, remember just about hundred and five years back nobody knew how to fly basically. There all surface transport only, but air transport was just not there.

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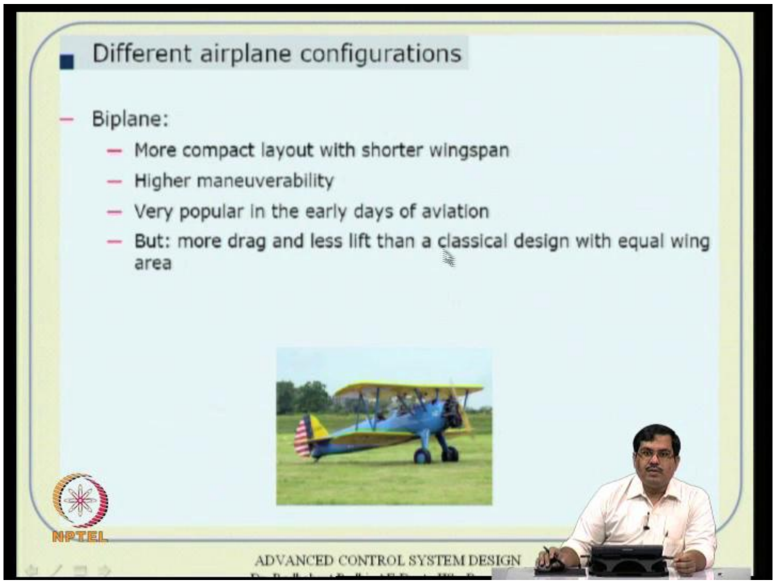

Now after that you can will we can skip a gap of about thirty years probably. Then, we will go little bit to the modern era. This is something which people started which is called as biplane. You can see that there are two wings here; one bottom and one top. Through that essentially creates additional lift to support your structure. At the expense of little bit additional weight also by the way. Because the most structure you add to the system the weight becomes more as well. It had high maneuverability; it was very popular in the early days of aviation. So, I mean sometime people even use this for war applications, involve war.

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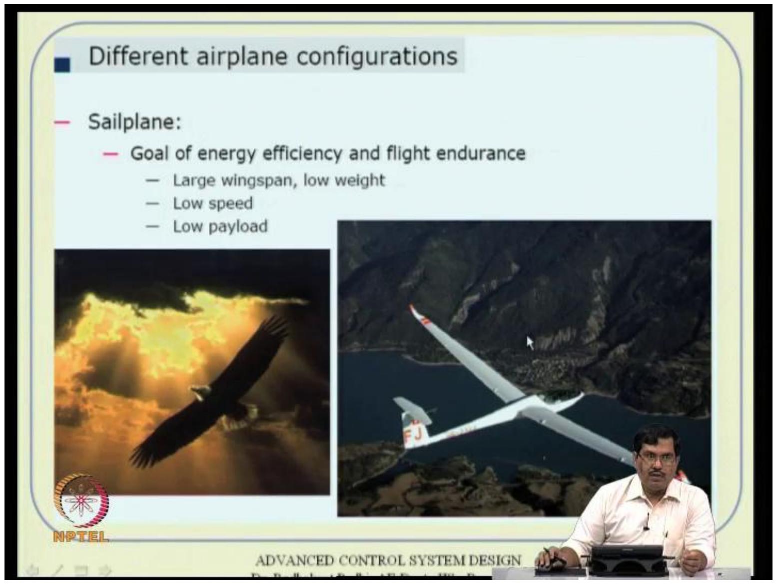

Then there are other applications, there are other many many designs has come up over the period of time. The next thing probably you can see is this is a very long wing essentially mimicking eagle flying. If you have eagle flying, I mean they just we can constantly do that. This is something called high expect ratio that means the wing span is very long. So, it has I mean it has it is a very efficient wing in that sense. However it cannot fly at low altitude and things like that. It has to fly at a relatively high altitude and it has a low speed, and it can also take low payload. So, these are like various consideration point of view people will use many many different things. This is I mean, this is just what I give here is just a small glimpse of things, largely collected from internet, so this part of it.

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Then coming to commercial aircraft, this is the best possible aircraft available in market today, commercial aircraft the airbus three eighty. The strong competitor from that is going Dream Liner which is being designed 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 so, that is invariably there in all aircrafts by the way. But the moment you lift to drag ratio becomes more and more, your efficiency of flying efficiency of the aircraft design is higher. So, then in addition to that you also look for high fuel efficiency, high reliability and safety requirement. You carry so many passengers out here in a regular basis.

So, you cannot compromise in safety issues and also remember these are all long flights as well. So, you really require a good handling quality, so that pilot can fly it in a good way whatever he expects the aircraft response that way. And then, there is a strong requirement of passenger comfort as well. So, the too much of vibration, too much of oscillations are kind of not required out here.

All weather operational capability is a requirement for airline operation, profit operation and all that. However you remember the speed and agility or what you known as what is known as maneuverability are not that critical out here. You can nicely take off, go, land and as long as you maintain safe safety requirements and passenger comfort, good handling quality and things like that then you are very much. And on top of that, you have to assure that the aircraft design is very efficient with good engine quality also like fuel efficiency has to be very good here.

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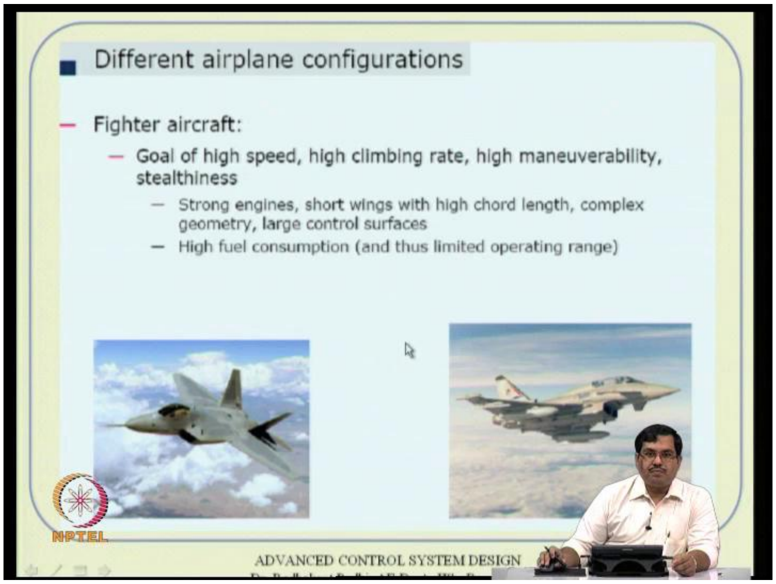

Then coming to the next class, this is a fighter aircraft. There is a slightly role reversal out here. What we really require is high speed, high climbing rate, high maneuverability, stealthiness and things like that. So, here efficiency and is not that much important. If I require I can pay a little bit extra money for may come back to superiority. In case I have to overpower (( )) so, for that I require all this actually. So, then these are typically characterized by very powerful engines.

There short wings, high chord length, complex geometry, large control surface. Because you really require high maneuverability I mean high maneuverability that means high control (( )) and things like that. High fuel consumption is also there, and hence it is some limited operating range as well. Remember, it cannot carry heavy amount of fuel either basically. So, all this limits operational range, so there are there are concepts like I mean refueling the aircraft to on the fly. That means as it flies it can be refueled as well actually from an oil tanker and things like that.

So, there is a complete role reversal here compare to commercial aircraft to fighter aircraft. Commercial aircrafts are purposefully designed to be very stable and kinds of robust application have to requirements and things like that. Here it is purposely made unstable and control surface, control design, makes sure that you with I mean the close system becomes stable, because open loop is unstable here.

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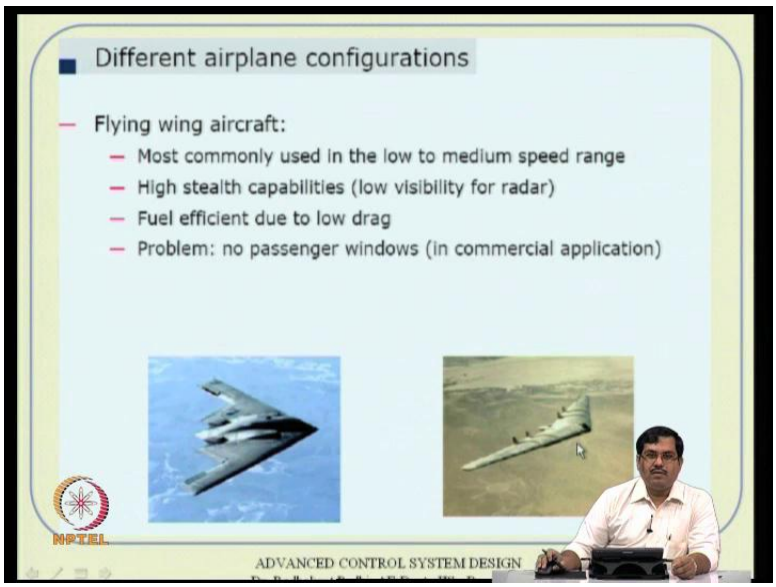

Then, there are various other designs. This is something called flying wing aircraft. That means, you can visualize the entire thing as a single wing and these are all requirements from stealthy considerations. It is a high stealth capability that is low visibility to radar. Fuel efficient, it is also fuel efficient due to low drag. Typically it flies at very high altitude. So, the air density is very low, dynamic pressure is low, drag is low. We will see that just little couple of slides later.

And normally, I mean this is a 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 hole, 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 thing. So, that is not very popular among passengers.

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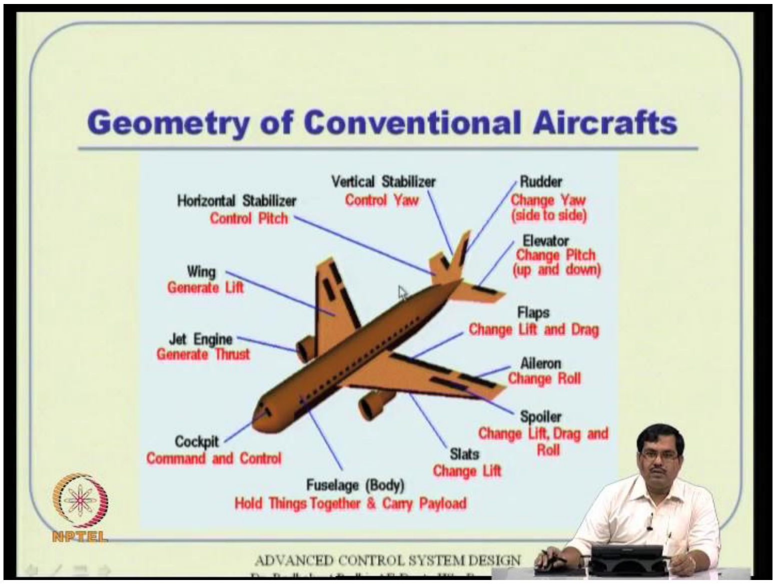

Now coming to the conventional aircraft geometry, if you see the aircraft geometry there are various parts of the aircraft that is specific requirements. It is a complex system of course. It is first of all engines which is required for propulsion, it has a huge fuse law sort of thing where people can sit, move around and things like that. That is where people sit two wings here which largely are responsible for this generating lift.

And they are then, they are like cockpit here where passengers I mean pilot sits and there are whole lots of instrumentation out here. And after that there are a lot of control surface arrangements. So, this is something called this particular thing vertical stabilizer, this is horizontal stabilizer the entire thing. And then, within that there will be like cut outs here which can actually deflects left and right that way.

If you see this particular thing, it can deflect left and right; this particular thing, it can deflect up and down and things like that. So, then there are other arrangements like what is called a spoiler slats and there ailerons, there are like flaps out here and things like that. There is a huge number of control surface that goes on here essentially as part of the wing or vertical or horizontal stabilizers. And there will be cut outs which can move up and down or left and right. So, through that the controls moments keep generate and how it is done, we will see that here.

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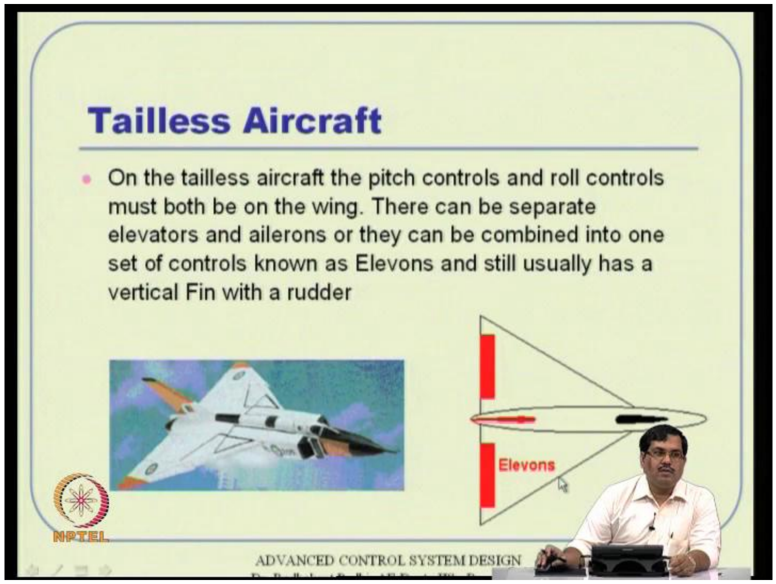

Coming to a different class, there is a tailless aircraft. What you see here is a complete tail arrangement. There is a horizontal stabilizer is a vertical stabilizer out here, but in this one there are no such arrangements out here. There is no wing see if go there is a clearly, there is a big wing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

So, the shock wave will get generated and all that. That should not heat the wing; it should go outside the wing. So, once the shock is generated here, it will something will like this. It will go outside the wing, it will not touch. Anyway, so that is one reason of that there are other reasons as well. What happens here is, the pitch control and roll controls that is typically done through the pitch control is done through elevator and roll control through ailerons. There are done together out here, what are called is Elevons?

If the differential, if the deflected in a symmetric way they serves as ailerons. If they are deflected in a symmetric way, that is one up and one down then they serves as ailerons. So, that is the reason for what is called is an ailerons plus elevators, elevators plus ailerons that is Elevons.

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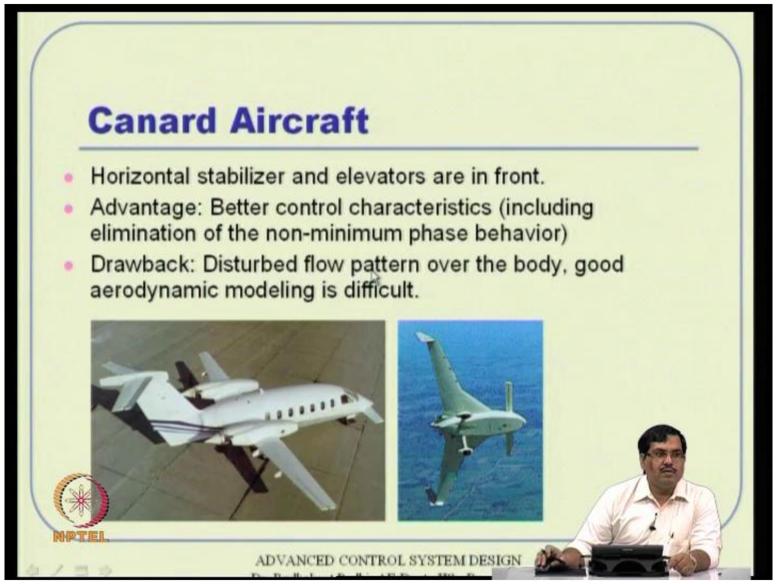

So, there are varieties of things. Another thing that is people have attempted is something called canard configuration. That means instead of a wing, I mean instead of a control surface at the back, they want a control surface in the front. That is something called canard structure. Again inspired by some fish design and some like some fishes have this structure, how they control their movement and all that and some birds also have this.

So, what it 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 we will see it later that, if you have an elevator in the back that actually creates a downward force first. If you really want to go up if you really want to go up these needs to be I mean you need to create a force downwards. So, that this entire there is a moment upwards. So, the entire aircraft actually kind of rotate upwards, and then it generates lot of lift out here. We will see that mechanism couples of down slides down the line.

How that means there is a force that creates that is created downwards first here to rotate the aircraft in a positive sense. So, that means this entire body of the aircraft essentially first goes down and then goes up. That is the nature of what is called is this non-minimum phase system. So, that is kind of avoided here, because if you really want to go up, you create a force up. So, that if you create a force up out there, then there is a moment also upward.

So, then there is no movement of going down and then going up. It simply starts going up and up. So, that is that you eliminate this non-minimum phase behavior characteristics. However drawback, it the flow out on the aircraft gets (( )) distracted, because see anything happens at the tail the air flow is from front to back. So, anything that you do here the flow disturbance does not affect the body, the flow on the body.

But here it is not so, it actually affects the flow on the body. That means the aerodynamic modeling becomes difficult. So, that means your control characteristics will be good, but you will be working with a model that does not have good fidelity. That means you again compromise on that aspect. So, that is the… so there are various structures that are available. These are this is so only a simple few glimpses out of that. Now coming to how these I mean how this objects fly in the… let us see that. Basically, there will be like force and moment balance. Let us study what is force balance first.

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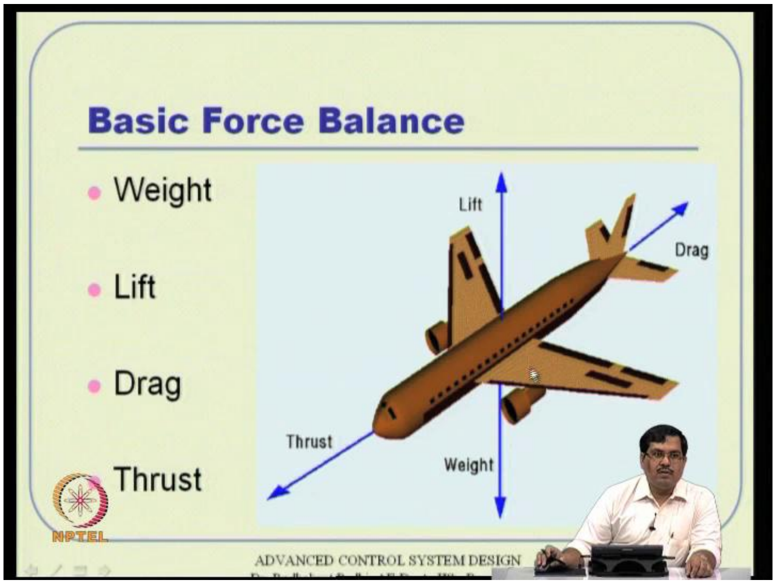

So, any flying object in a straightened level flight, let say has to counter act I mean this four forces get generated and they balance each other. First thing is there is a weight component which is vertical. So, there must be a force which is upward which should counteract that. So, there is a weight which is balanced by lift, but this lift generation mechanism also creates a drag. There are there is I mean we will see that the reasons for (( )) drag, drag is a force to the back.

And hence, even if you want to go in a constant velocity constant you have to constantly cancel out this force, this drag force. That means you really need a force to the front (( )) . So, there are four forces essentially in a straightened and level flight. One is weight which is balanced by lift, and then there is a drag which is balanced by thrust. So, we need to see how these forces are generated. Weight is obviously it is very obvious; this is a mass and then there is gravity. So, because of that m g force is acting downwards that is kind of obvious.

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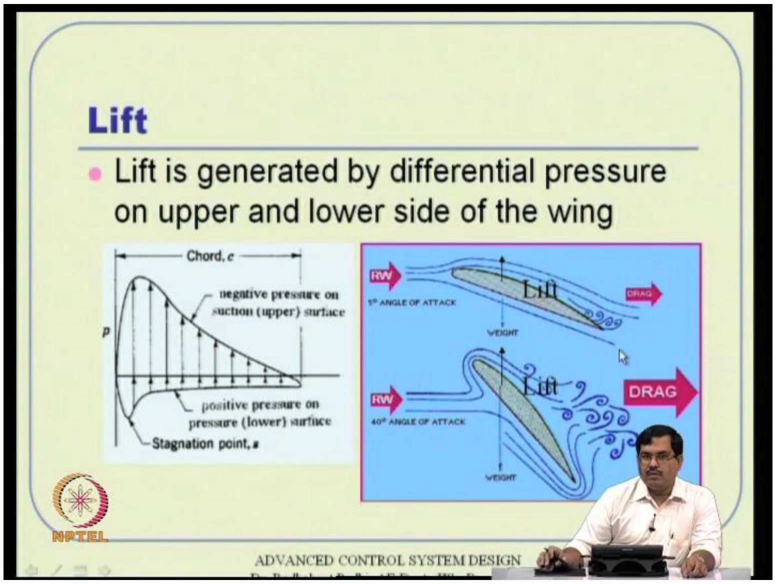

Let us see the other three. First thing is how to counteract that by lift? How do you overcome effect of weight by lift? So, lift is generated by differential pressure on upper and lower side of the wing. If you see the wing structures, there are varieties of structures, if you see there. And once the aircraft starts to flying front that means you can visualize that the fluid flows backward. For this is one and the same things imagine a case, where your aircraft moves through the fluid or fluid moves through the body.

Aircraft that is normally done in internal testing also, the aircraft is kept stationary, but the wing wind is flown over that. Essentially what matters is relative velocity. So, if you see that the flow it starts from left and goes to the right probably. And then, because of there are this flow filed characteristics and all that all details will be there in aerodynamics and things like that.

We will not go too much into detail, what happens here is because the way these wings are designed and you see some sort of a thing called angle of attack. That means there is an 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 high pressure acting in the bottom, and then there is low pressure acting on the top.

So, if you see there is a differential pressure which builds on here. And if you integrate over the entire area, what happens is you get a force, net force upward that is what lifts is. And remember, if this angle is larger and larger this is a smaller angle, five degree angle of attack and this is very large angle forty degree angle of attack. What happens is you can get higher lift and upper limit of force. And after that again, these lift fellow starts decreasing basically. So, essentially what happens is if you increase this angle keeping your speed constant, then you can increase the lift. But the prizes to you will your drag also becomes more and higher. So, that is the drawback.

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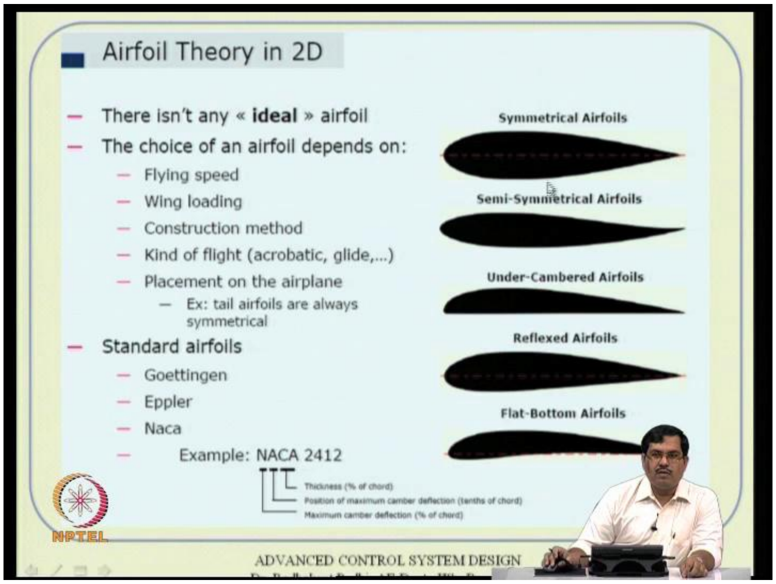

So, going to little bit on this aerofoil theory, but aerodynamic people call there will be various suppose I take a wing and cut it through basically, vertically. Then I will see something like some sections like this and these sections play a very good role in generating lift. And there are variety ways of designing that and different applications. So, that means the bottom line is there is no ideal aerofoil airfoil. Depending on what application you are talking about, you will probably select an airfoil that is best suitable for that application.

So, choice of the airfoil depends on flying speed, wing loading, construction method what technology you have, and kind of flight. What kind of flights you are talking about? Placement of the … I mean placement on the airplane where you want to place the wing? And things like that. So, that are variety of studies including Wright Brothers themselves studied a lot of things. But after that there are a lot of studies about that and varieties of wings are available now days.

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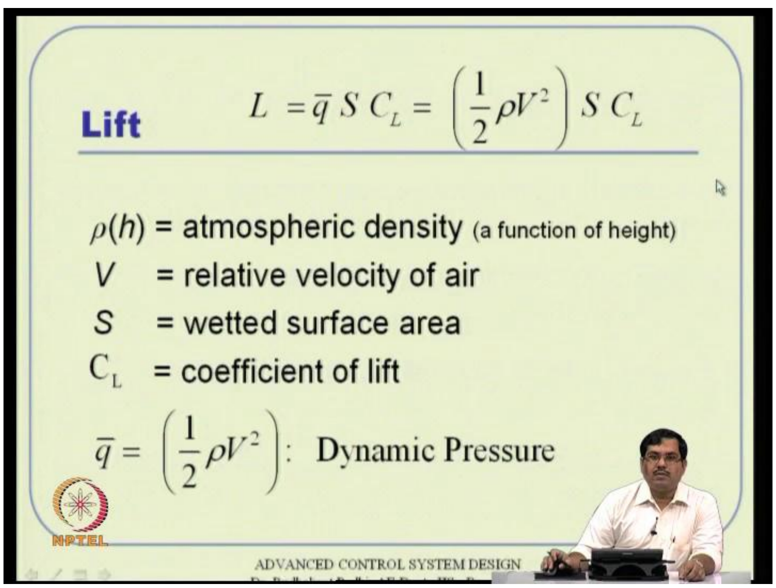

Now coming to the mathematics part of it, what is what is beauty for people like us in control system is this lift to expression if you see. This is universally saying, this is something given like this. This q bar is something called dynamic pressure given by half rho square, S C something called weighted surface area of the wing. These are typically surface area is given to a particular, it is a number given to us from aerodynamic people for a particular aircraft configuration.

Then rho is obviously atmospheric density and it is a function of height, we will see that how it varies. And then, there is V square which is relative velocity of the air with respect to the vehicle. So, this term is a dynamic pressure, this is surface area and this is C L which is lift coefficient. Now do you no matter whatever aircraft you talk about, whatever design of the aircraft, whatever speed regime you talk about let us say supersonic, subsonic whatever flow pattern anything. Any flying object the good thing is lift expression does not change. Expression is given like this, where all other affects are imbedded into C L.

That means the model that will be giving to us typically will contain some expressions on C L depending on the application that you are talking about. And that may be you like given in the as a table of data and things like that as a function of mach number, as a function of angle of attack and things like that and that can change. But the entire the overall formula will not change. And that helps us quite a lot in control design and all that.

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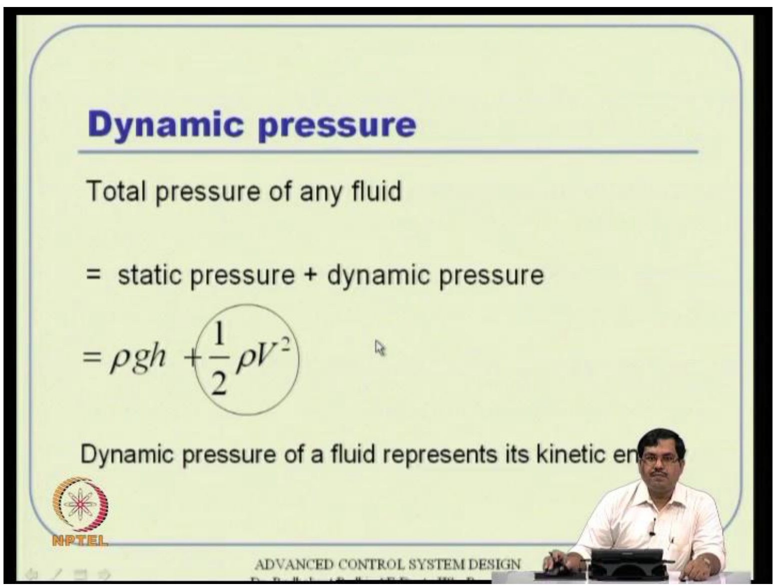

Now coming to the dynamic pressure part of it, what we saw here is half of rho V square dynamic pressure. And this dynamic pressure is actually we can visualize the total pressure of any fluid is partly from static pressure and partly from dynamic pressure. The static pressure is rho gh that this potential energy sort of thing. And then there is a dynamic pressure which is essentially kinetic energy contained. So, this is what plays a role in generating lift and drag essentially.

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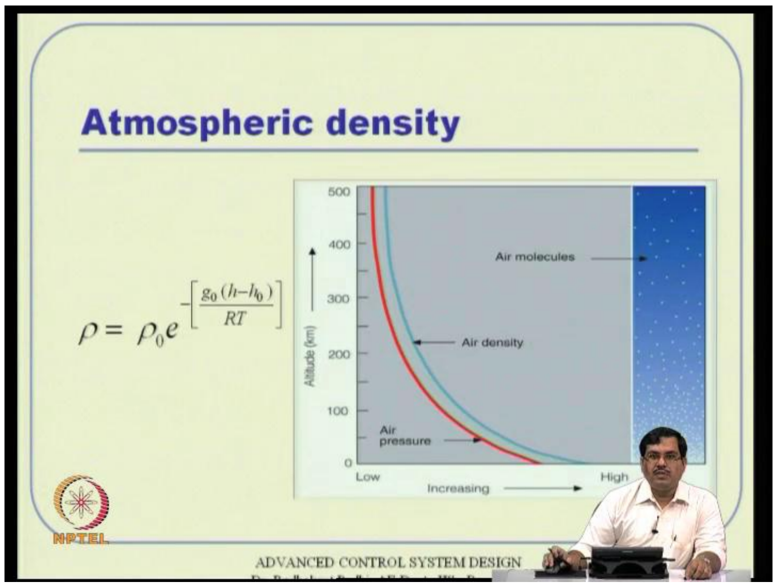

So, atmospheric density if you visualize I mean universally this remains true by the way. If you see this distribution of air molecules on surface of earth, they are very dense. As you go up and up, they are very sparse. And that is probably because of gravitational affect. The surface of the earth, the gravity is very high. So, see lot of air molecules concentrated on surface of earth. Once it goes up and up, they are getting more and sparser.

So, essentially what happens? The air density decreases exponentially, so you can visualize this plot something like increasing values being like this, the altitude becomes more and more; your air density starts decreasing. What you see here is altitude, so if you go up and up your density of the air becomes low and that decrease actually happens in an exponential way. Your atmosphere density is roughly given by this formula with a negative exponential. So, what happens here is the more you more height you climb, the dynamic pressure becomes very low, I mean lower and lower. Ultimately, it becomes very low and you will not be able to support, support your weight. So, that is why there will be altitude ceilings for any given atmospheric flying objects and all that.

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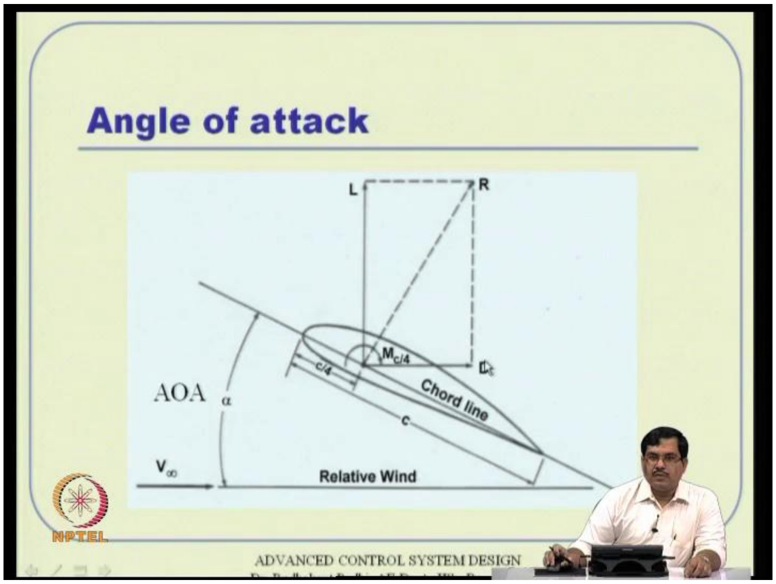

Anyway, so angle of attack formal definition, this I told this is free stream velocity and there is a mean chord line. If you see take that angle, then that is an angle which is called angle of attack. And that plays a very critical role in flow pattern distribution. As you saw that here, that is angle of attack flow pattern entirely depends on that quite heavily. And that angle plays a very important role in C L essentially.

C L what you see is as C L here. That will be typically functioning of alpha. And then, this is this one fourth of the chord line something called center of pressure. This is where if you take incremental pressure or incremental force and then sum it up, then the moment becomes zero out here. That means the entire lift and drag gets generated out here, this is called center of pressure basically.

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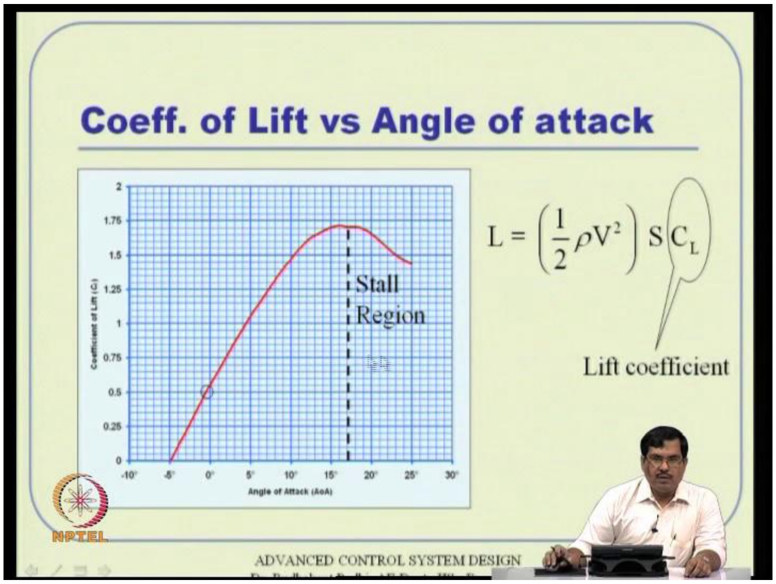

Now coming to the gross behavior of C L versus angle of attack, this is what happens? It starts like a fairly like a straight line. But at high region, it goes stabilizes and then it decreases. This is something called stall angle of attack roughly of the order of seventeen, eighteen, twenty degrees depending on airfoil, what airfoil you are talking about? Also remember that when angle of attack is zero, you still have a positive lift. Only when the angle of angle of attack is some negative value, then only you will have something like lift zero out here. So, any for positive for zero angle of attack, you still have some lift generation.

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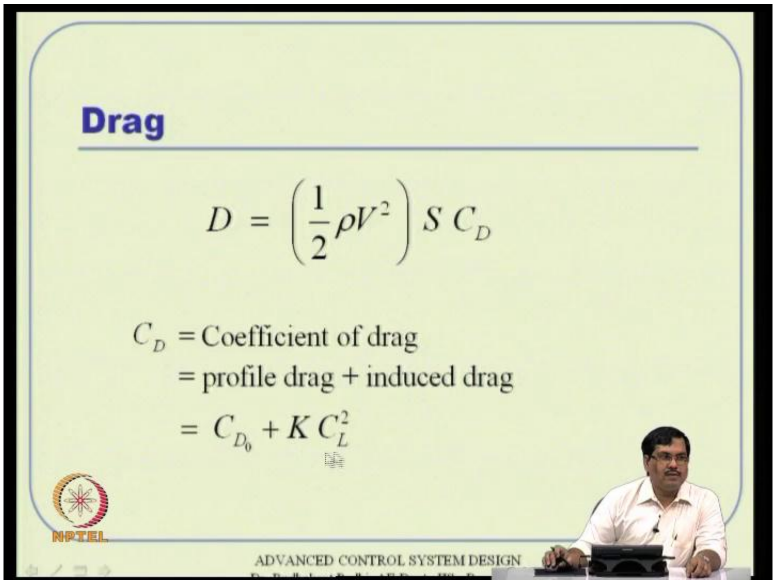

Now coming to the drag part of it, the drag is also given by very close formula instead of C L what you replace is C D. But also remember that C D is roughly a function of like this function of C L in a quadratic way. So, C D is essentially C D 0 plus K C L squared; that means it varies in a quadratic manner basically. So, any amount of lift that you generate, this additional term keeps on building. And also remember, even if you do not generate any lift even if C L is zero, still C D will be there. But drag will be in variably there.

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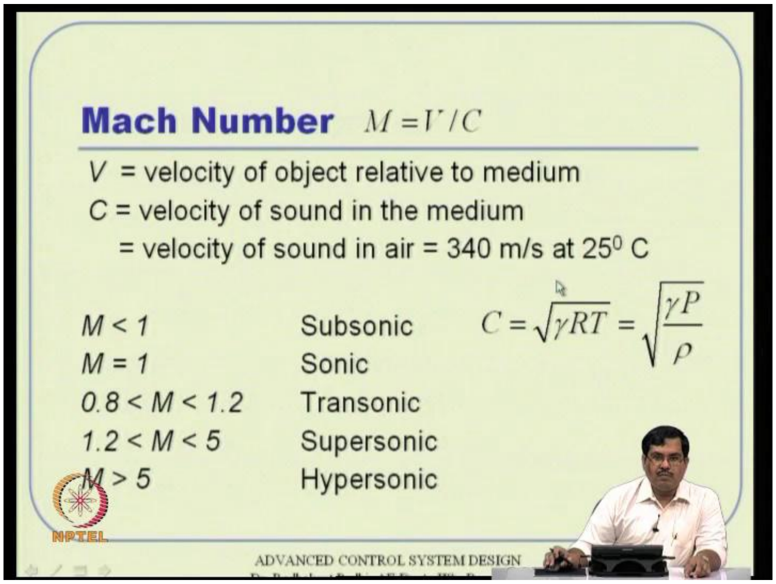

Now there is another variety of notions that are avail I mean that are required in flight dynamics understanding and all one of that is called as Mach number. And this is a non-dimensional quantity; this is essentially defined as velocity of the object relative to the medium whatever your flying object velocity divided by sonic velocity. That means velocity of sound in the medium at that particular condition. So, velocity of sound is also function of height, remember velocity I mean it does not remain constant. But if you talk about 25 degree centigrade and things like that formula is given like this. And it is largely a function of air temperature essentially and also remembers temperature of air also varies along with height.

That variation is not given here, it does not very exponentially decaying manner, but does vary with height as well. So, it remains like at sea level at 25 degree centigrade room temperature and things like that, you can take this value as 340 meter per second. Now what is beauty of that is this particular number plays the heavy role in defining what is called as sub sonic speed, sonic speed or transonic, supersonic, hypersonic things like that, because the aerodynamic behavior is a strong function of this Mach number.

So, as long as you have subsonic speed, there will not be any shock of generation. Your aircraft velocity is lesser than speed of sound. Wherever whereas, any supersonic thing and hypersonic thing they will create shock waves. 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. These are some of the reasons why this Mach number plays a heavy amount of role. And also remember, C L and C D are typically functions of Mach number.

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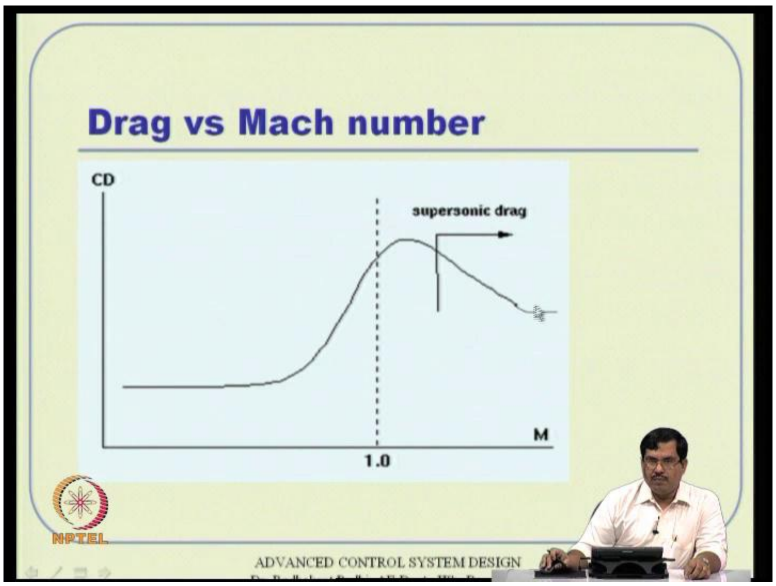

Now CD how it varies with Mach number is something like this in a subsonic region, this is a fairly constant value. Essentially, what you are talking that C D 0 portion? Now K C L spectrum, then it starts building of very fast. Then, it will again decrease and it will stabilize after some time after high speed like about Mach number one point five two, there onwards this fellow will not change.

Also remember that this number where you stabilize is higher than this number. That means if you really want to fly a supersonic speed, then your drag is going to very high compare to subsonic thing. That is why this commercial aircrafts are very successfully in subsonic region. The moment you go to supersonic, the efficiency goes down. That is why this Concorde aircraft was very expensive to fly. That was supersonic aircraft was very unsuccessful commercially basically.

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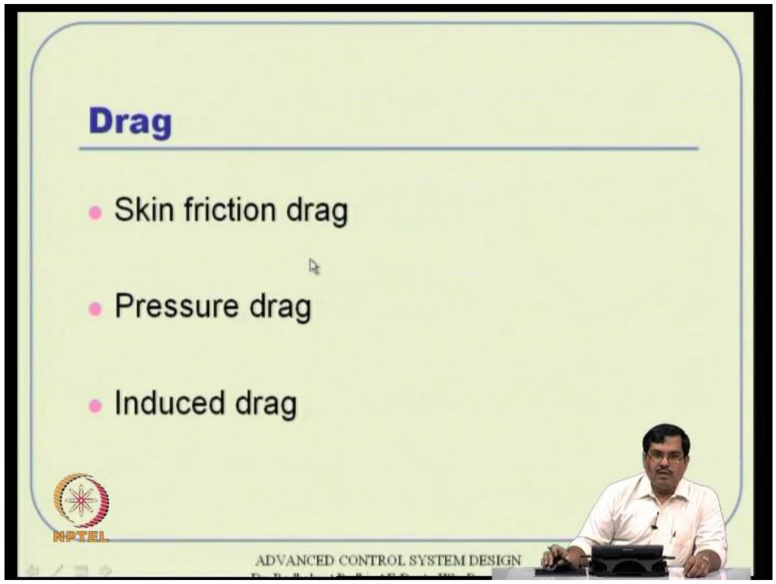

Now coming to drag components, you can visualize why this drag is coming? There is something like skin friction drag, pressure drag, induced drag, and the various other components as well.

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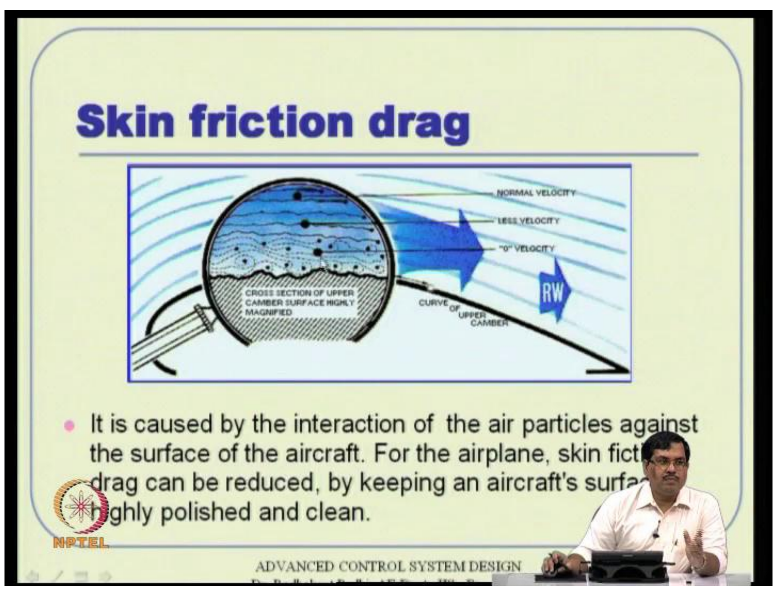

Let us see very quickly, skin friction drag is essentially because of surface area non-smoothness. So, if take a very big microscope you can see what you what you feel like smooth surface is not really very smooth. It is some I mean surface roughness, because of that there will be local circulations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

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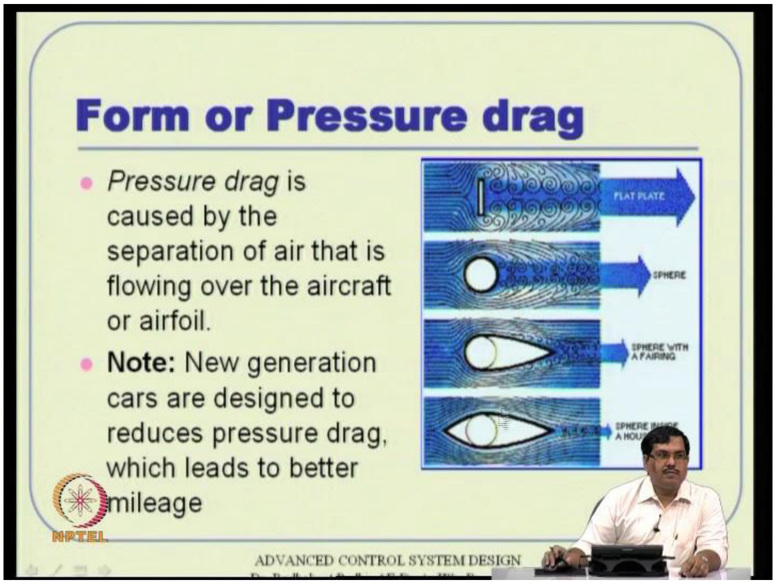

Now form pressure drag or something, it depends on the form of the object suppose you take this vertical plate sort of thing that will where your drag will be maximum. Because the entire flow pattern is completely disturbed after that. Then, if you take a perfectly spherical object sort of thing things are slightly better. Then, if you take this particular form shape then this is still better. And if you can optimize this particular design, then it can be very I mean very good compare to all other thing.

So, that because of that region is see this new generation cars expensive cars, but comes with that they also go for some sort of aerodynamic design. Because once you see speed of the car is higher and higher, you essentially land up with this pressure drag. So, to minimize that you see there is a typical shape of these cars will be somewhat like this somewhat last two sort of thing new cars that comes there.

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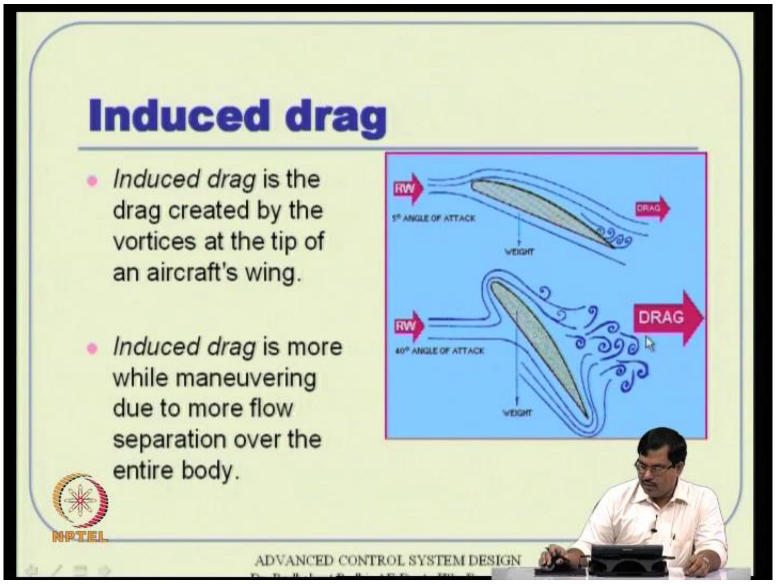

Now induced drag is essentially we discussed about that as I mean, this is primarily because of flow pattern dispersion. Because of these vertices, that is that gets created I mean afterwards. As that angle of attack is more, this flow pattern as this vortices generation is more. So, you get induced drag more and more and this is also a function of flow separation over the entire body that happens more while maneuvering. So, if you are flying straight in level, then the aircraft structure is designed to be optimal in that mode, any time that takes a turn the entire flow field is distorted. So, you will have more and more vortices generation and things like that, so in this drag will be more and more.

So, it is a strong function of your, what is called as later oscillation. So, the moment you generate a later oscillation or normal oscillation as a way, then it will have induced drag component will go more. So, one of our control design method, so we will see later in I mean if covered I will we will see later that this missile guidance application particularly I mean I do not know whether I will cover that in one of our lectures or not. But one of the reasons one of the objectives there is to minimize the induced drag through an optimal way of latex generation. That is one of the conditions that we lead too and essentially this, what is called as p n guidance which is very popular in missile guidance that implicitly does that anyway. So, those things are there.

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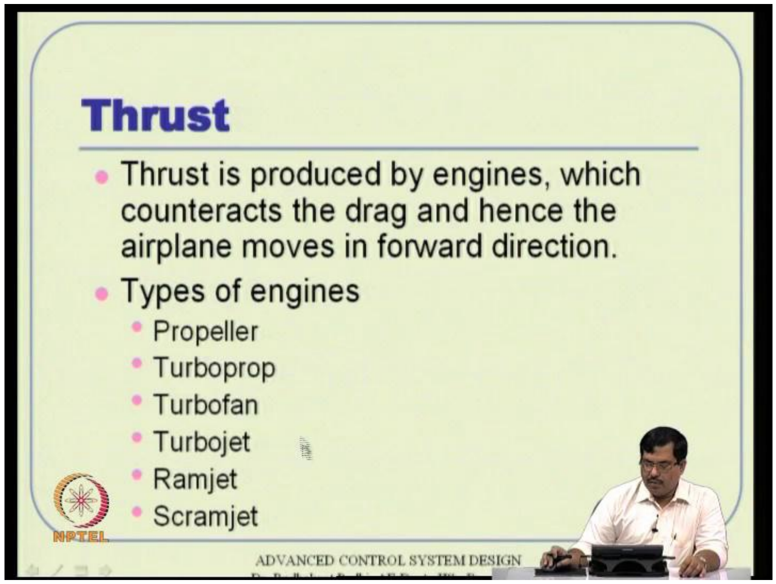

Now coming to the thrust force, so you remember there are we talked about weight lift, weight versus lift and drag versus thrust. So, this thrust generation happens through variety of through variety of ways and you have to essentially use an engine to do that. And it can happen through a propeller through a turboprop, turbofan, turbojet, ramjet, scramjet in a variety of things which are field by itself.

We are not going to discuss too much on that, what we are what we really need is a trust generation mechanism in the in control system design. As well as, it will limit strength this thrust generation mechanism will also give us some sort of control force. We can manipulate the thrust required, the magnitude as well as the direction to a limited extend. This is a thrust vectoring what you call in fighter aircrafts. So, these two are these are possible I mean available however variety of ways of generating thrust.

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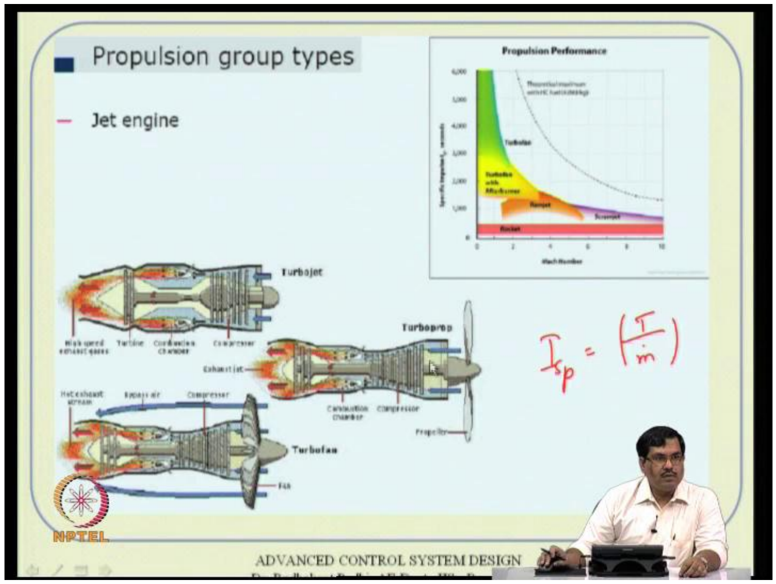

Let us very quickly see that jet engines can be classified into like turbojet, turboprop, and turbofan things like that and this is roughly the behavior what you expect. I do not know whether this slide is not very clear. So, what is plotted out here is Mach number versus specific impulse I s p. And this I s p, this is by definition something like thrust by mass flow rate. So, how much flow is there, how much fuel spend essentially it generates that much of thrust, that kind of an idea there. So, if your I s p is higher and higher your engine is operating in a good efficient manner. But unfortunately what happens is if you really want to fly with Mach number higher and higher that is no more possible.

So, if you see this kind of this class of vehicles, what will operate on turbofan sort of idea? They operate on very low speed, Mach number less than one. So, we are efficient, I s p kind of high actually there this region what is our … On the other hand, this is what is rocket engines rocket engines are very inefficient, their I s p is very low. However you can fly with whatever Mach number you want, Mach number nine, ten whatever you want. You can go through whatever degree of speed you want.

There will be something in between there some concepts of something ramjet, scramjet and things like that. This is because of something called ramming effect that is the name ramjet comes, supersonic combustion ramjet that is scramjet and things like that. So, there are essentially varieties of this modern aircraft essentially works on either turbofan or turbofan with burners like things or sometime they work with turboprop as well. And some applications we will see.

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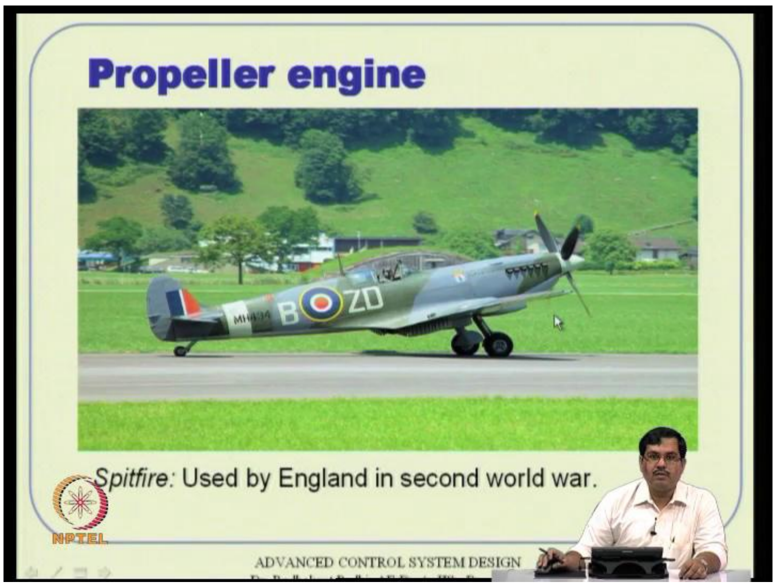

The propeller design, propeller engines are essentially old ideas and there one example is this aircraft which was used by England Second World War. So, it was in practice, it was operational successfully.

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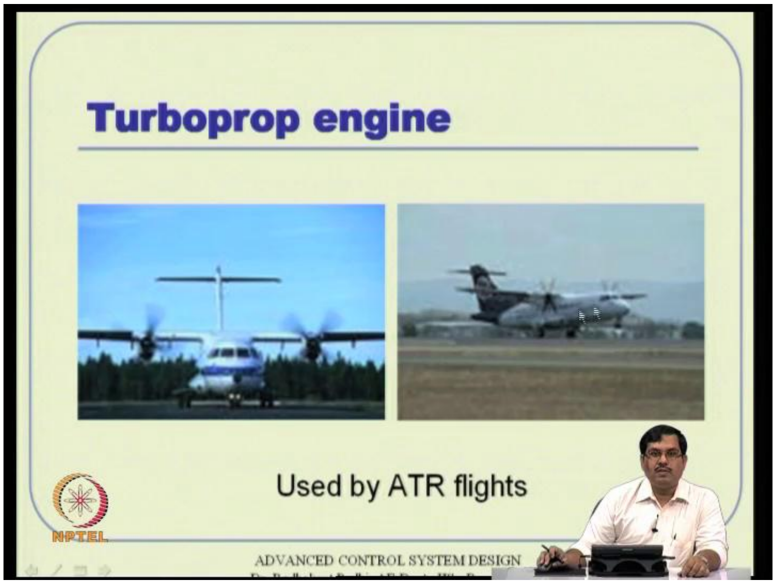

Turboprop engines you see even now there many ATR flights that we take short duration flights as with less and less number of passengers and all. They are efficient in that region. This essentially operates in that region like this turboprop variety sort of thing. So, ATR flights do use turboprop, this is I think many of you have seen this in airports and probably many of your flown also.

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Turbofan engines are typically used in big commercial aircrafts and turbofan engines remember are less or less very less noisy. Because the entire rotational mechanism if you see, they also go inside the casing basically. So, that they are both efficient as well as less noisy. So, that is the where you see these are used in commercial aircrafts both big aircrafts basically. For example, A 380 is that.

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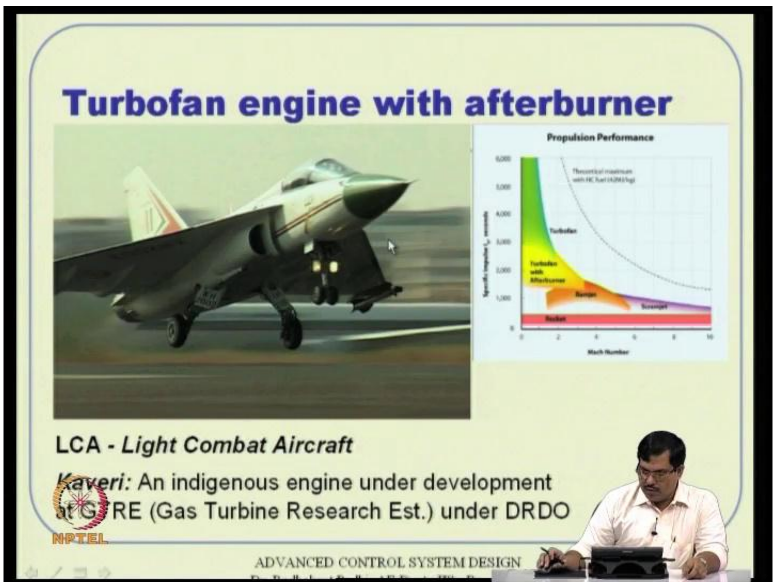

Turbofan with afterburner, afterburner essentially remember if you see go back to this flowchart turbofan with afterburner is this region. Whereas, only with turbofan is that region. So, if you really use afterburner you can push that velocity to Mach number to supersonic region. So, you your I s p will be lower that means your engine efficiency will come down, but vehicle speed will be higher. That is where your fighter aircraft for example, LCA will use that, this is a light combat aircraft designed by actually.

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Ramjets engines are used in essentially they are used in missiles. Ramjet engines operate somewhere they are very low specific impulse basically. So, that the attempts are being made to make it commercially successful as well. But because of this they are typically a concern. So, they are supersonic I mean this is something called ramming effect basically. When your vehicle velocity is more than Mach number one, you are in supersonic region. You really do not need too much of this complex mechanism what you see here. There will be like compressor is not needed, turbine is not needed like that.

So and then, but the shockwave management becomes a critical issue there. So, shockwave management, shockwave both inside the engine and you really do not I mean have that much liberty here to manipulate as you want. So, there are critical technologies out here. And then, still further technology boundaries towards that I mean this is not successful yet however people have only test flown and demonstrated for short durations that you can even go up to Mach number 9. That has been demonstrated by NASA in that X-43 flight.

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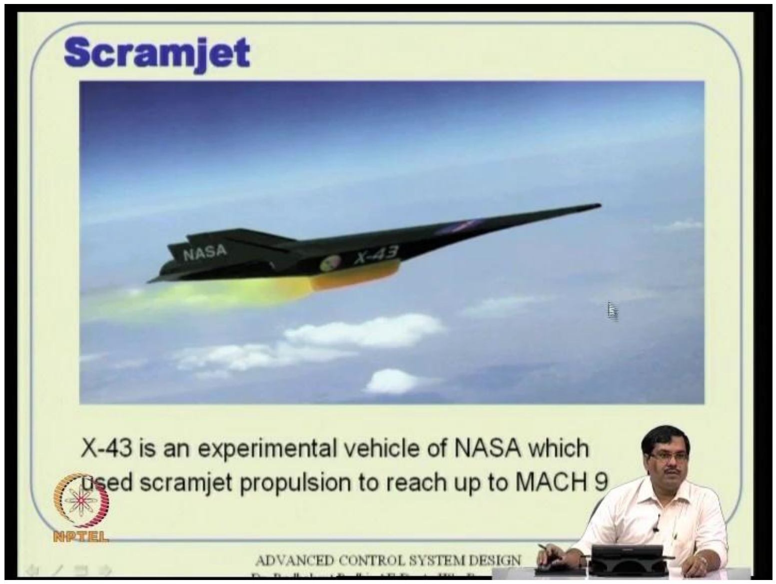

This is a missile operating, this real missile operated I mean developed jointly by India and Russia. It has been test flown and being inducted. So, this is so varieties of missiles are available which will really operate on ramjet principle. This is just one of that. Now coming these are all, so called force balance we studied. Now let us see very quickly, what is moment balance as well. That is moment is also a critical in a flying object. In essentially, moment is the one which gives us controlling capability of a vehicle not force; force gives us propulsion characteristics and all that. But by changing the moment changing the rotational behavior, we will be able to control the vehicle. That is where we see that.

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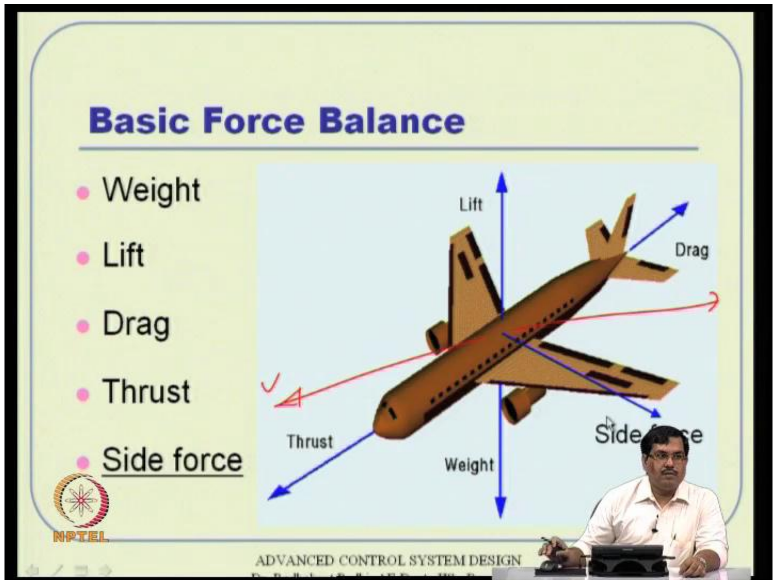

Now just take a quick review, what we saw their force balance is weight lift drag and thrust. Also remember that, there will be a side force component that we typically neglected assuming that to be zero there. So, this drag is not perfectly, you see thrust is normally aligned perfectly like to the nose sort of thing that design. But drag, you do not have a choice typically. Drag is actually opposing to the velocity vector, and the velocity vector all the time need not be align to the vehicle nose. They can that can go somewhere inclined. And once it happens that way that is the velocity vector sort of thing let us say. The velocity vector is somewhere something like this, this is velocity.

Then there will be opposing force which is there and that you can resolve into two components. One will come that what we have seen as 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. So, in general we do not want side force generation. That is what is called as like term coordination, coordinator term and all that, we will see that.

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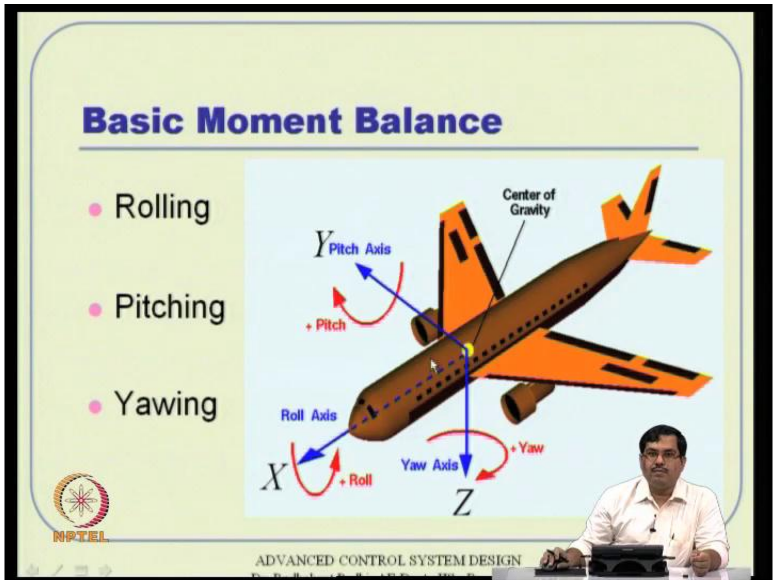

Anyway, so the basic moment balance is essentially three moments are there; one is rolling moment, another is pitching, another is yawing. Essentially, this is something called body axis. You can visualize an axis frame sitting on the center of gravity of the vehicle where X axis is pointing to the nose; Y axis is to the… what is called as star board or right side of the wing. And then, there is like the vertically down is something called Z axis. So, any rotation if you can graph that axis that way, pointing to the right or whatever this is this side this side is your like thumbs will point out. And then your other fingers will point in that direction. Thumb is in the direction, this will become in that direction. And this is the positive rolling moment.

Similarly, if you graph this axis your thumb pointing towards that, then the other fingers wherever they point that is called pitching action. We will see that one by one here. But see that first is roll, rolling is about positive X axis which is above positive Y axis, and yaw is about positive Z axis. So, roll, pitch and yaw those were very critical in control system design application as well, I mean we will see that.

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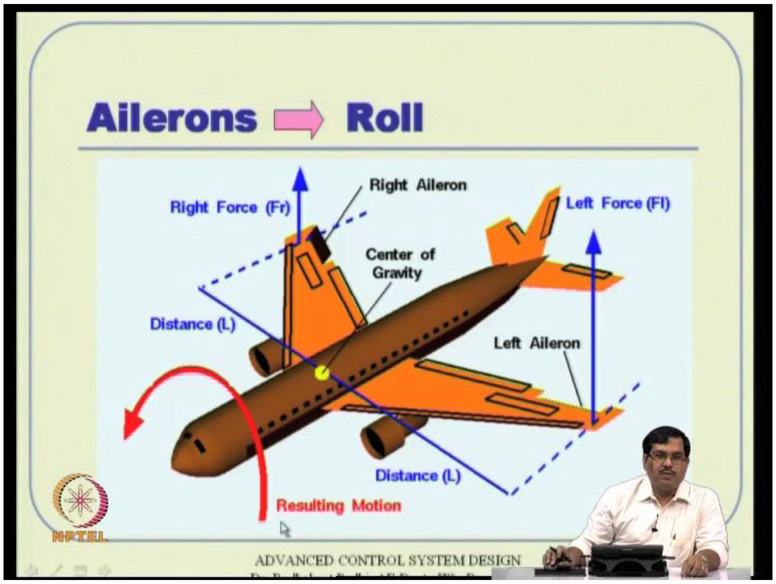

So, what is how do you create a roll motion, rolling motion? Suppose you really want to cancel the unwanted roll or you want to create a wanted rolling thing, you want to take a turn then you have to create a roll as well. Rolling and yawing are typically coupled. If you see this roll and yaw are typically strongly coupled, whereas pitch will be decoupled from these two normally. In general all three are coupled. But these two are strongly coupled even in a linear setup we cannot neglect the decoupling part of it, whereas this part is fairly decoupled from these two. Now how do you create a rolling motion is essentially done through create a creation of differential force through this cut outs. What is called what are called as ailerons?

So, there is a cut out here in the right side of the wing, and there is a cut out here in the left side if the wing. Suppose your left side you turn it down, and then your angle of attack essentially goes a little bit of higher in the side. That means your lift C L becomes more, so you get a larger lift force here. Whereas you get, you defect in the other side you get a lesser lift force out here. Because angle of attack, the effective angle of attack you are reducing by deflecting it up. By deflecting it down, you are increasing the angle of attack, so the lift force becomes more.

So, what is happening in larger force here and a smaller force here? So, that means there is a differential force which is not on c g, it is far away from c g. So, it will create some sort of a moment, some sort of a moment here actually about c g. So, that effect let us see. So, the moment you try reflect like up and down that will roll like that, this aircraft. This effect is called rolling effect.

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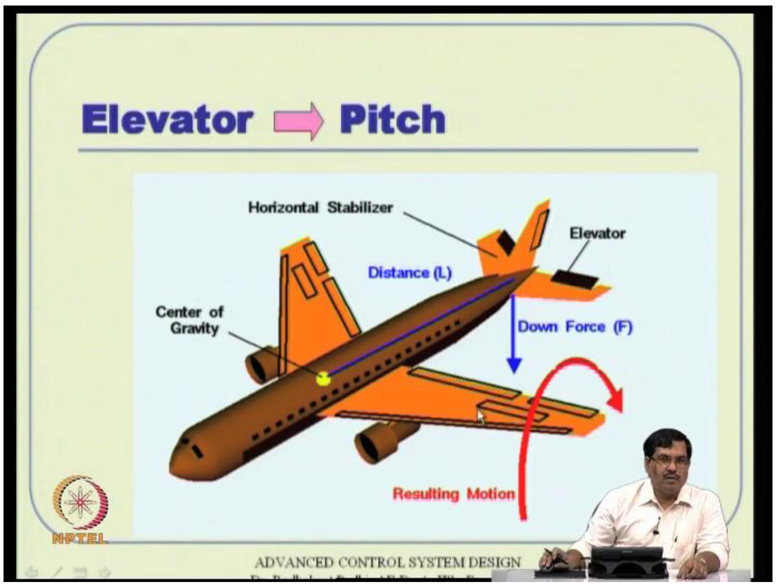

Similarly, if you see the pitching moment how do you create a pitching action? Is largely through these elevators? They are reflective symmetrically either both up or both down. Once they are both up, then you have an essentially there is a downward force, they are differential downward force remember that. They need not be the complete downward force, aircraft need not go down. But there is a slight downward force here, but it is far away from c g remembered this length is very high. So, you get a large moment which gets generated out here. So, then that will create some sort of an upper moment, the pitching action basically. That will happen while reflecting the elevators.

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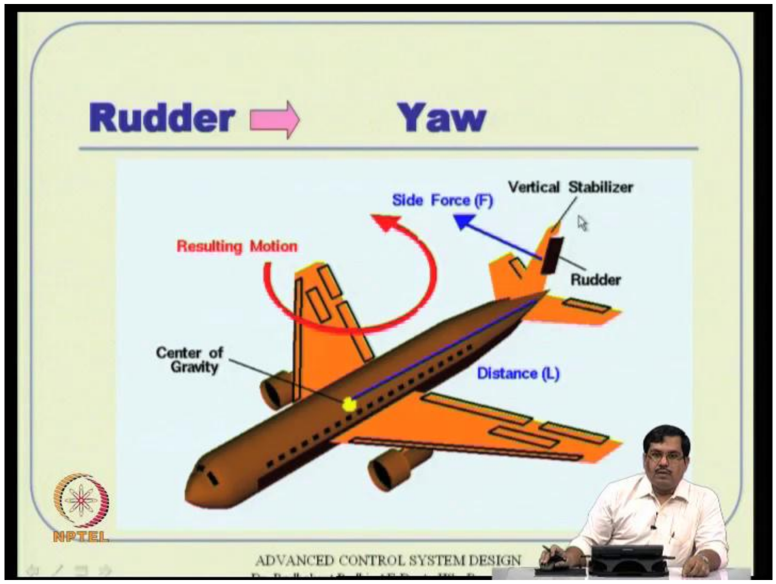

And similarly, the yawing motion is typically controlled by rudder. Rudder if you generate left or right, so there will be a side force generation essentially. So, that side force will create a resulting motion in a yawing sense. By the way, this rudder is also used in nullify this side force that I talked. 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 these control surfaces are very capable of generating heavy amount of force.

They generate a small amount of force, but because the moment arm is long, the moment creation becomes strong. So, this is what happens through rudder moments. Now coming to that this motions what you see neat neatly, these are coupled motions. These are not decoupled motions. Let us see that one at a time again. You have this three axis- X Y and Z. Any moment, this moment or rolling action above this is called rolling. Angular motion about this X axis is called rolling action.

Then angular moment motion angular movement 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 like there. For controlling the yawing, you have a rudder which is right here.

Now there are additional things as you know these are flags and these are spoilers, and these are slots 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 whether to … for example, if you spoiler you can just you cannot make it down. It is on the surface of the wing, top surface of the wing. So, you can only take it up, but that is once you do that what happens is there is a heavy amount of drag created.

And these are done not differentially, they are done symmetrically. You cannot do it differentially anyway. Differentially you can do you provide deflect this one two degree and that one five degree. That is a different issue. But typically both have to go up, one cannot go down and one cannot go up that way. Once you take both up and with equal angle, then what happen? This moment that you generate is counteract by that moment. Essentially moment generation will not be there, but what will happen is there will be a force generation. That is an additional drag will create that is typically use while landing the aircraft.

Once you those of you who have flown the aircraft when see landing carefully outside the wing, you will see that during landing after touch down the suddenly these guys go up to create heavy amount of drag is essentially like a breaking mechanism. These slots what you see there, they are reflected onwards typically to have more flow attachment, so that your lift becomes more. So, that happens during essentially takeoff and landing. Lift becomes more, drag also becomes more in that way either way whatever way you want.

While taking off you want lift more, while coming down while touching, you wants drag more… Flaps are also deflected vertically down that way. So, there are 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 only called trim tab. So, if you really want to fly on a trim condition, then not only this has to go down. But that little portion at the end of that particular surface will go up. So, these are variety of considerations we will see in a flight mechanics course.

This is not a flight mechanics course. 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. That means whatever forces you see here like they are not separated by from each other at all. So, that is that is how it is a non-linear coupled equation and there are three axes you remember that. On the three axes, you will get like three forces and three moments. And all of these forces and moments are governed by Newton's second law.

And each Newton's second law is m h double dot remember that. So, once you have double dot formulation, essentially you can convert that into state phase form in single dot, two differential equations. So, what essentially you have is twelve differential equations, three axes, three forces and three moments six actually six each are second order equations. That means, you will get six into two equal to twelve equations in total. So, those twelve equations will be coupled with each other. And that are the equations I mean that the set of equations are the one that we are going to use in non-linear control design for flying objects in general and aircrafts in particular.

We will see those details little later. And there are varieties of other things 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 over a long duration. You really do not need to care. As far as trajectory optimization or as far as guidance problem is concerned, you 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 matches?

As long as I go close to the target I am okay. As far as guidance problem is concerned, they are typically will use point mass equations, not so much detail. But, when you come to control design in a good way, you really have to use what is called as six drag equation. That is what I just talked about. Three axes are there and three forces and three moments, and each are of second order equations. That essentially consist of what consist you would say six degree of freedom equation of motion. That is what you will be used for control design in general. So, all these things we just saw that one more time let us say.

This is aileron for rolling control that is what will happen. These are remember, these are getting reflected the dark ones, the solid ones. The ailerons and this is elevator, these are the ones which are used. That is how it will be used that. And this is a rudder thing which will if you reflect left and right that is what will happen. This is called yawing motion.

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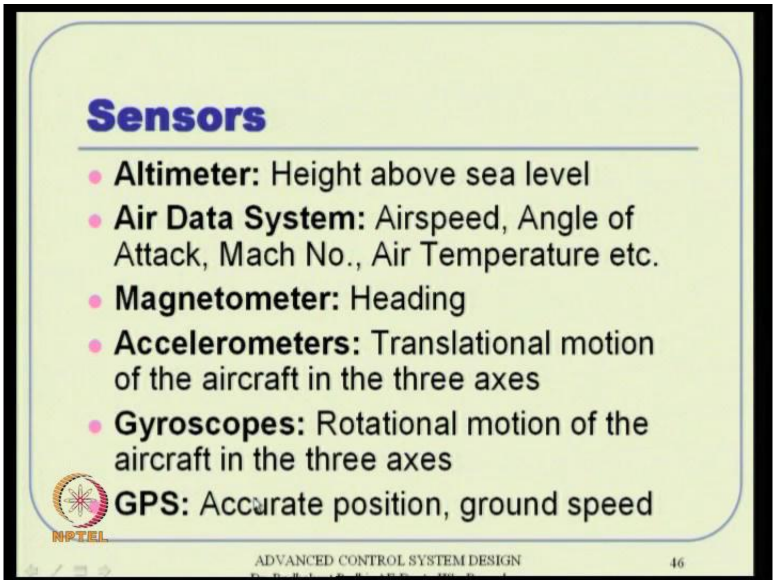

Now coming to the sensors also remember that when we talk about automatic control of aircrafts, we really require a heavy amount of sensors to what goes on in the vehicle. And it is a very sensor rich system rather the modern day aircraft in a sense whatever we talk about. Launch vehicle missile so even satellites, all these are very highly sensor rich. And in the sense, you can get the same information using multiple sensors as well. That gives us sensor redundancy that one fails other is still there.

It also gives us data fusion capability. That means if you take one measurement through one sensor and the same measurement using three or four sensors. I can fuse it in a good way to get very good accurate information. So, all these are use actually now come what are the typical sensors that goes in an aircraft? You can think of first as an altimeter, you really need to know about what height you are flying.

Then there is an air data system which gives a host of information like air speed, angle of attack, Mach number, air temperature etcetera many things will come from there. Then there is a magnetometer sometimes use for heading things. Remember, if you put a compass sort of things, it will always point to the north. So, if you put a very good compass let us say on c g or something it will always point to the north. So, that you will know which heading you are going actually, what is the direction of your vehicle that is a magnetometer?

And all these have their own limitations and advantages. So, depending on what application you talk about? You should use sensor information in a clever way rather. And what is invariably there in modern day flight object I mean flying vehicles something called I N S system, inertial navigation system. And essentially that consist of accelerometer and gyroscopes these are invariably there.

Accelerometers are essentially the major translational motion of the aircraft in three axes. There will motion this like translational speed, translational isolation things like that they will measure that. That means along X Y Z axes, what you saw here? Along X Y Z there will be velocity component that are those are called u v w and things like that. Those quantities will be measured through accelerometers. And then, the rolling the angular motions and all they will be measured by this gyroscope.

So, rotational motion of the aircraft and three axes are measured by gyroscopes typically. Then there is another set of sensors which you call GPS global positioning system, they essentially operate through satellite information and all that. The twenty four satellites there up and then you acquire some four good satellites at any point of time around the globe 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 imitate that signal. And using that information, you calculate your own position in a very good way. It turns out to be highly accurate system. However it is subjected to signal availability from this from the rudder from the satellites.

And essentially that is control by US. So, there are also like parallel systems available like GPS called then called something are still getting developed like things like that. They are same concepts, they operate on two frequency band also; one is available throughout the world that is civilian frequency band. And the upper, there is also a military operation band which they 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 it is not available. But it is a highly accurate system, it not only it measures position it can also measure ground speed as well and things like that. This is not an exhaustive list. There are other sensors available as well.

Some for example, star sensors. These are available for altitude measurement, but they are they can be use (( )) that means for satellite application they can be used. That it is a technology by itself I mean in a huge way basically. And gyroscopes they can call mechanical gyroscopes, there are fiber optic gyroscopes, there are lesser gyroscopes there many things like that.

Accelerometer similar ways there are and there are for UAV applications, they are typically MEMS level, micro electro mechanical system they are manufactured. They are low cost, but not that accurate system. So, this is so what I mean is a lot of information will keep coming through a variety of sensors which will be essentially processed by your by onboard computer and to give a control command essentially.

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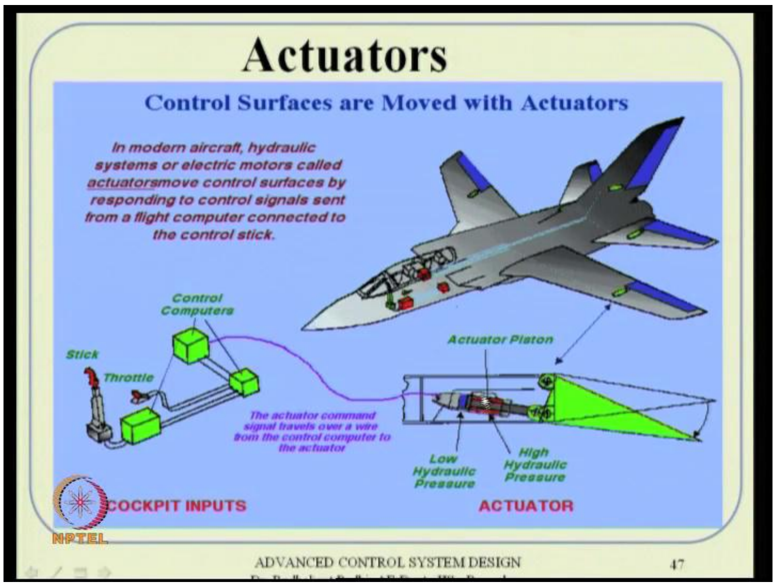

So that is ultimately executed through actuators. Actuator will be situated now modern day aircrafts, actuators are situated right there where you really need that. And the command as everything goes through all sort of computation through flight computer. Essentially the signal is transmitted through a wire to this actuator system which actuates the system, it reflects that ailerons for example. So, what is the require amount of computation that how much degree, how much reflection you need to give? That essentially computes using your flight dynamics, using your control system technology and everything.

Now, ultimately you give a command to this actuator. That actuator takes the command electronically through a wire and then executes it through some sort of like a motor and all that. Either it is a hydraulic system or it is an electrical system as well. This is because all these things happen through a wire, not through extensive mechanical mechanism. These are also called fly by wire control systems. Everything information is taken through a variety of sensors, their process through either through low pass filter or formal filtering whatever you want to do. Then that process information is used in flight control computer I mean control design algorithm. Ultimately this output of the algorithm is past back to this actuator and this essentially that is executed there.

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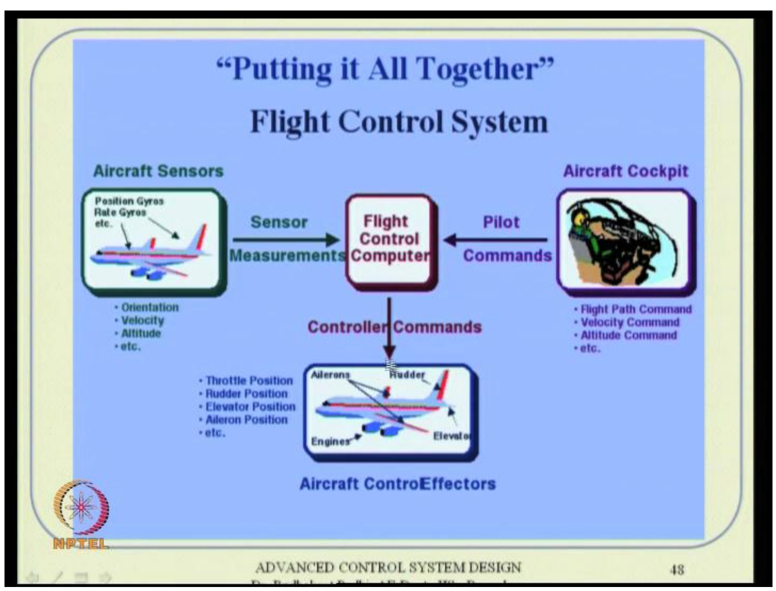

So in a nutshell putting it all together, there is a flight aircraft sensor which will sense the measurements. And there will pilot command also, pilot will see outside and all that. That also you can see that huge amount of sensors that goes through pilot organs basically like eye, ear, and talk all sorts of things. Then he gives a command essentially that also comes to the control computer. It goes through a variety of computation then it gives control command which is essentially executed there.

So, the entire control mechanism essentially deals with this flight control computer, what will deal here. We will talk about algorithm development essentially using the various variety of models the point mass or six drop or whatever. How do you generate a good control algorithm, which will essentially be given to the control or actuators essentially? So, that is our entire objective here in this particular course. This is where I will stop for this class. Thanks a lot.