Introduction to Flight
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Lecture: 11.5- Takeoff Performance of Flight: Part II

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Various speeds during Take-off Run

Ok, now we come to V1.

Video: Ok let us look at V1, imagine yourself in the cockpit of your plane, the plane takeoff first three engines and as you gently accelerate down the runway you come to a point where you reach V1. So by the book V1 is defined as the speed beyond which the takeoff should no longer be aborted meaning that in case you experience any trouble with your plane before reaching V1. Classic example will be an engine failure you would immediately abort your takeoff and will apply all the necessary methods to bring the aircraft to a stop. Although the use of full reverse thrust is not mandatory. I will come back to that in a second.

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So in this video here this Airbus A-319 applied apply takeoff first and due to a technical malfunction had to abort the takeoff prior reaching V1, just listen to the sound of the engine, Now the auto break system comes active and immediately applies pressure to the break cylinders, the ground spoilers are deployed so are the reversers and the plane comes to a safe stop on the runway.

The smoke you can see here is coming from the breaks as they are the primary force slowing down the aircraft. Now let us say there were to be an engine failure, so one of the reverses would be in operated and therefore full reverse thrust come the added to the breaking measures as mentioned before. Because we want needs to be calculated prior every take off taking into account airplane weight, runway length, wing flap setting, engine thrust used, runway surface contamination and environmental factors and even the aircraft brakes to assure yourself that any given failure prior reaching V1 you have enough runway leftover to come to the complete stop.

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Now if it is just a minor failure you can continue to take off but that is a whole another video about the stop or go decision making. And besides that this is one of the reason why the captain keep his hand on the throttle until the pilot monitoring calls out V1 and then he moves his hands away from the throttle to interdentally abort the takeoff after the V1 in case of a failure. So in case you experience any serious malfunction after V1, you would have to commit yourself to continue the takeoff otherwise a takeoff abort will lead to a runway over.

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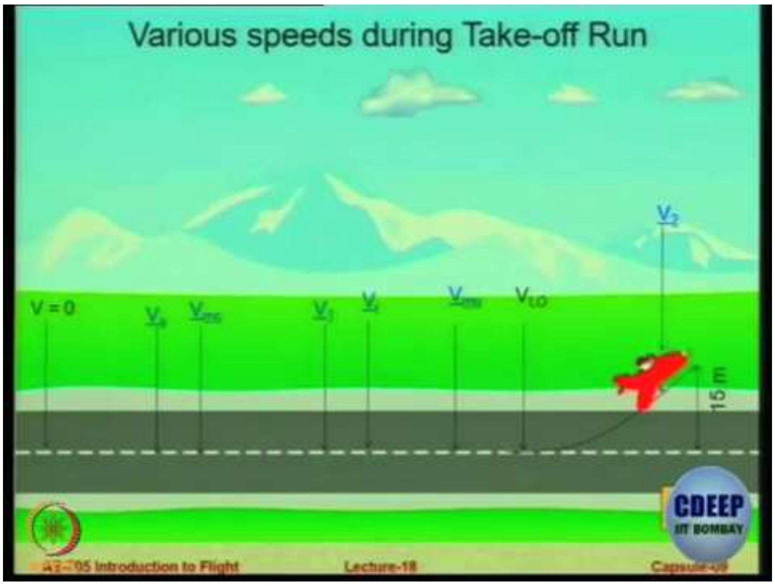

Various speeds during Take-off Run

Ok, so do you understand now why it is called decision speed? Because during take off if the malfunction, engine failure any problem is observed before V1, what is your decision? What would you do as a pilot?

Student: Abort it.

Professor: 100 percent right, abort the takeoff. Do not be a hero or do not try to be heroic or say oh I will take it, no. Decision is before V1 you have to abort, ok. Now if for some reason engine failure occurs, now in this case that we saw in that example, the problem was thrust loss. It was detected before V1, so the pilot applied full brakes, you saw brakes were fuming, ok. So when but then suppose a decision, suppose the failure is recorded after you crosses V1, what is the decision to be taken? Even though there is a engine failure you will continue take off? I admire your guts.

You have two engines and one engine has failed, it has failed after you have crossed V1, why will you continue? Yeah let me ask this captain. Why would you continue takeoff after V1?

Student: Because then we won’t have enough distance left on the runway to stop and will exceed the runway.

Professor: Correct, so the numerical value of V1 is decided based on this calculation that if you abort take off after you have crossed V1 you may still be on the ground but if you abort after V1 then the accelerate stop distance it is called. From start to the end, accelerate and then brake, that will exceed the safe runway available.

Now this safe runway is a very big word. I will have to explain it to you, in an airport you just do not have a runway, you have a runway, you have a clear way, you have a stop way, apart from taxi way and airplanes. So a runway is basically the hard surface, which is designed to take the impact of the aircraft when it comes in to land, ok. The stop way is an the additional part of the runway may be not as hard as the runway to take impact because you do not land on that but you may exceed runway and go to the stop way for a accelerate stop distance and the clear way is nothing but an area under the control of the aerodrome during which obstacle height can be cleared by the aircraft, ok.

So clearway can be ground, it may not be even paved, it may be grass, but it is the are which is under the no construction is permitted beyond a particular height, in fact nothing is allowed to be there except required by functions, some instruments for navigation, some antenna, some lights etc, ok, but otherwise clearway is supposed to be clear of all obstacles, fine.

So therefore if the problem is detected just beyond V1 you are not supposed to abort your takeoff under any circumstances. What happens if the problem is detected at V1, now what would you do? Before V1 it is clear, after V1 it is clear but it is suppose at V1, most pilots will abort, but you can do both, it is the intersection point. So you will not be charged if you continue takeoff at V1, but most pilots will not, they will discontinue, ok.

So now let us go to Vr, Vr you know is the V rotation speed, the speed at which the aircraft can be rotated for takeoff. We call out as Vr or better known as V rotate, by the book Vr is defined as the speed at which the pilot begins to apply the control inputs to cause the aircraft nosed pitch up after which it leaves the ground again Vr is also calculated prior takeoff in accordance with the aircraft weight, environmental factors, etc and it is the point where the generated lifts over the wings becomes higher than the aircraft weight keeping it on the ground.

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Easiest way to remember Vr is point where the nose will leave the ground and vortex are created at the wind tips which rotate behind the aircraft and the point where the main gear leaves the ground that is the point where you have reached V lof, ok. So V rotate is when the nose wheel has left the ground and V lift off or V lof is where the main wheel leaves the ground.

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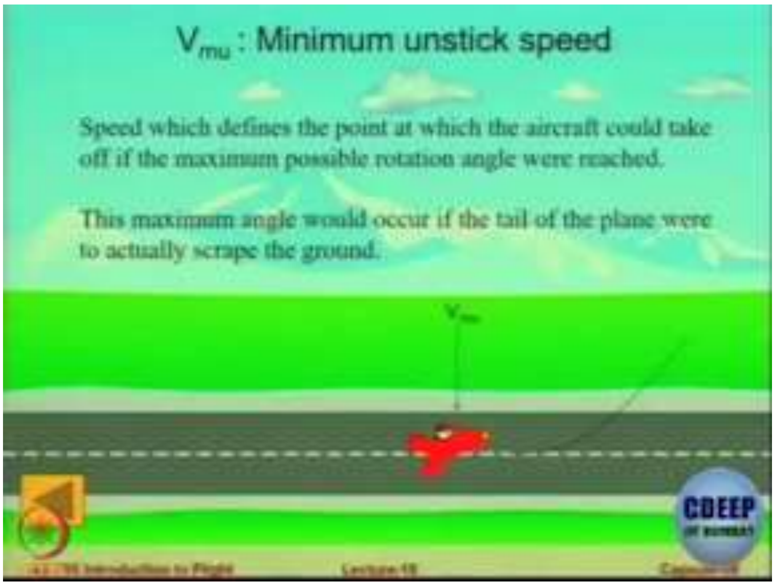

V_{mu} : Minimum unstick speed

Speed which defines the point at which the aircraft could take off if the maximum possible rotation angle were reached.

This maximum angle would occur if the tail of the plane were to actually scrape the ground.

Then we have V mu, minimum unstick speed, ok. This is the point at which the aircraft could take off if the maximum possible rotation angle were reached. Remember there is something called as stalling angle. So when you rotate you cannot exceed Alpha stall otherwise it will stall. So if you reach Alpha equal to Alpha max permitted, which is below Alpha stall, then at this speed or at this minimum speed the aircraft will generate lift more than weight that is the definition of V lift off. And this particular angle could be limited not only by aerodynamics but also by geometry.

For example, you may be able to go at a higher angle, ok, Alpha stall may be 15 degrees but Alpha for minimum unstick could be 12 degrees, because at 12.1 degree the tail will hit the ground because of the geometry of the aircraft. So it could be limited by geometry or aerodynamics, normally by geometry. So basically it is the maximum permitted angle to be given during rotation.

So what is the minimum speed at which max permittable rotation angle will give you the lift off, that is called at the V minimum unstick. Pilot should know this because the pilot should not try to initiate rotation at a speed below this, because at a speed below this if you initiate rotation you will hit the ground before lifting off, ok.

Then we have V lift off or V lof then finally we have a speed called V2 take off safety speed. The takeoff safety speed V2 is defined as take off safety speed. The speed at which aircraft may safely climb with 1 inch inoperative , ok.

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Let us go back to all engines operative now imagine all is you know is take off and someone would measure your height above ground at the end of the runway like in this picture here, the height measured is the so called screen height. Now let us get back to V2 and our engine failure situation.

In case one engine fails you need to maintain the speed of V2 in order to leave the runway at a screen height of 35 feet or high and maintain the climb rate at V2 to be clear of obstacles in the departure sector and you should be able to maintain that speed and climb rate until reaching 1 inch now acceleration altitude where you then gain speed and retract the slats and flaps and continue with the emergency procedures.

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This video here is a great example for V2, as you can see the boing 757 hit a bird, so you see there is a bird which comes in the path, the engine starts getting flame so the engine starts getting fames, the engine has flamed out. The pilot maintained V2 and the respective climb rate, retracted the gear and perform all the necessary emergency procedures flew a traffic path and landed the airplane safely.

The reason therefore is when local authorities design departure rules including obstacles avoidance procedure, they predict that your aircraft is at least capable of maintaining V2 with one engine and the gear retracted and guarantee obstacle collision protect.

Ok, you get the point, I will show you this again, you can see this video.

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Continue with the emergency procedures. This video here is a great example for V2, as you can see the boing 757 hit a bird, and just after lift off and the engine was severely damaged, the pilot maintains V2 and the respective climb rate retracted the gear and performed all the necessary emergency procedures flew a traffic path and landed the airplane safely.

The reason therefore is when local authorities design departure rules including obstacles avoidance procedures they predict that your aircraft is at least capable of maintaining V2 with one engine and the gear retracted and guarantee obstacle collision protect.

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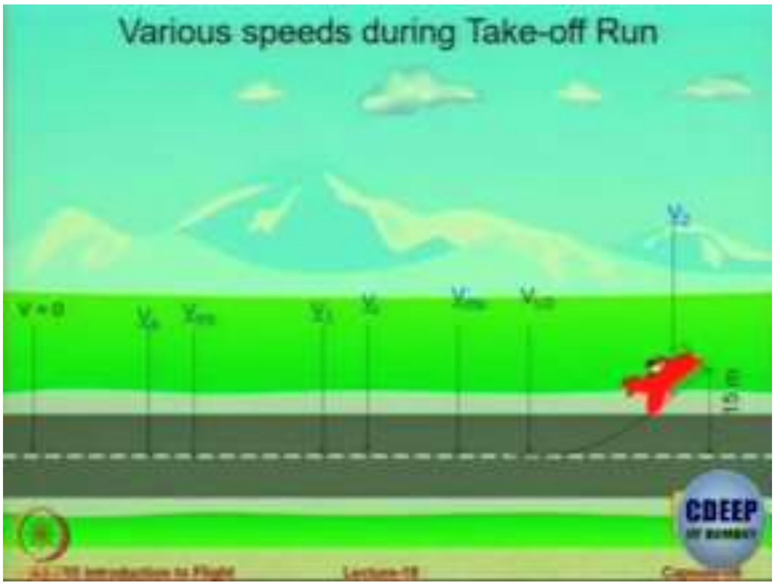

Ok, so V2 is the takeoff safety speed. It is the speed at which with one engine in operational you still are able to maintain climb rate such that you clear the obstacle height at the end of the runway, ok. In the example shown the engine failure happened before rotation, in the video it was after rotation but in the example, in the description it was engine failure took place after V1 but before rotation. So obviously when there is only one engine, one engine not working you will have less thrust available, so the climb rate will be lower, so if you have what is the speed at which with landing gear retracted you are to maintain the required climb that is called the takeoff safety speed, ok. So these are the speeds which we need to remember during the takeoff run.

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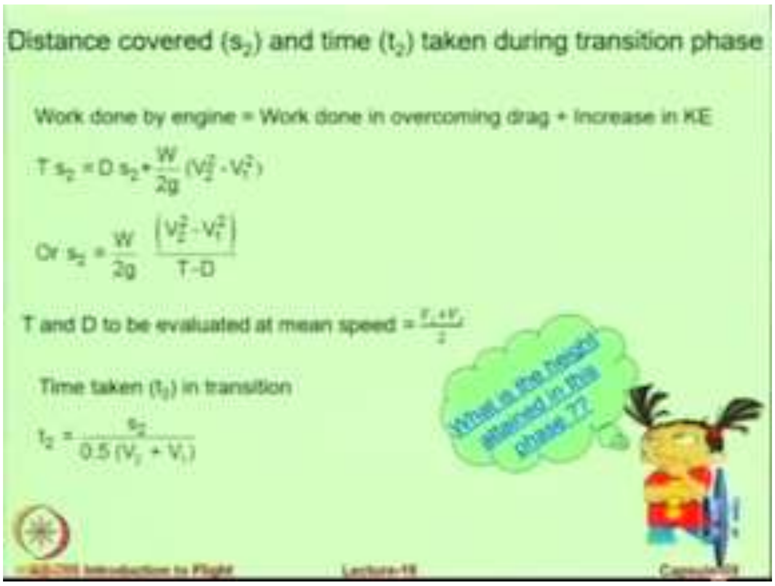

Distance covered (s_2) and time (t_2) taken during transition phase

Work done by engine = Work done in overcoming drag + Increase in KE

$$T\,s_2 = D\,s_2 + \frac{W}{2g}\left(V_2^2 - V_1^2\right)$$

$$\text{Or } s_2 = \frac{W}{2g}\,\frac{\left(V_2^2 - V_1^2\right)}{T - D}$$

T and D to be evaluated at mean speed = $\frac{V_1 + V_2}{2}$

Time taken (t_2) in transition

$$t_2 = \frac{s_2}{0.5\,(V_2 + V_1)}$$

So let us look at the distance and the time covered in the transition phase. So during the transition phase what is the profile flown by the aircraft, is it a straight line? Is it a curved path, is it a concave path or a convex path? What do you think? What is the flight trajectory during the transition? I showed you a figure of an aircraft during takeoff, it goes like this and then like this and then it climbs.

So the climb is straight line, ground run is straight line. What about transition, it is a curve, so is it a convex curve or a concave curve. If you are looking from inside it is a concave curve, right. It does not go this way, it goes this way. So to calculate the distance and the time taken during transition you have to assume the thrust is equal to drag plus the kinetic energy that is increasing and the time taken will be average of because speed is V1 and then V2, so the time taken will be the average because speed increases from V1 to V2.

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Hint: The height attained during transition phase can be obtained by treating the flight path as part of a circle

So this particular calculation now there is a height that is attained in this phase, that height is basically the obstacle height, ok. So this is something which I want you to do yourself. So I want you to model, what you will do is I will give you a hint. You can model the flight path or the trajectory of the aircraft as a part of a circle, ok as a arc of a circle, it is an assumption, actually it is not an arc of a circle but one can assume it to be arc of a circle.

So from speed V1 at the beginning of the arc of a circle to a speed V2 at the end of the arc of a circle, the aircraft is proceeding from a speed from V1 to V2. You have to now calculate what is the height that is travelled? So this is homework and I expect you to upload this homework on Moodle ok.

So once again the first person who uploads is ok, the second person should not copy paste or give the same, the second person should give the same thing in some other way, if not do not need to upload, ok so I leave that to you.

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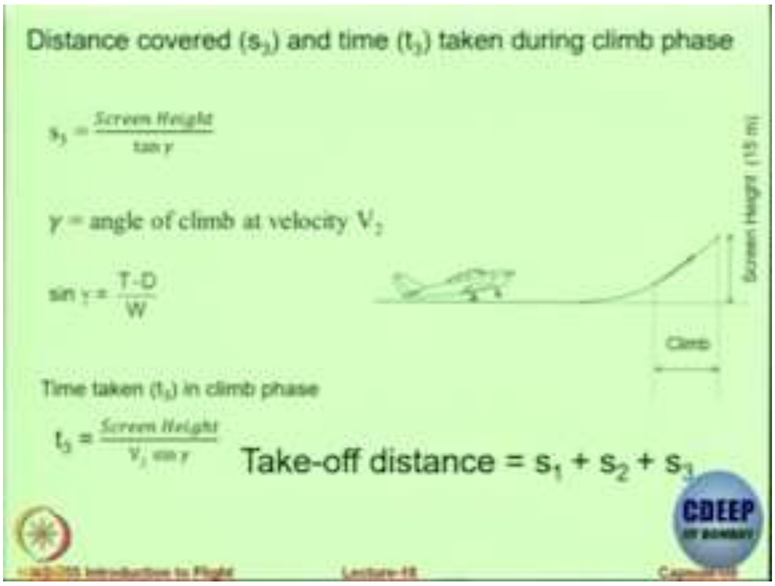

Distance covered (s_3) and time (t_3) taken during climb phase

$s_3 = \frac{Screen\ Height}{\tan\gamma}$

γ = angle of climb at velocity V_2

$\sin\gamma = \frac{T-D}{W}$

Time taken (t_3) in climb phase

$t_3 = \frac{Screen\ Height}{V_2 \sin\gamma}$

Take-off distance = $s_1 + s_2 + s_3$

Let us look at the climb phase, climb phase is very straight forward. During the climb phase you are in the straight angle climb, so you have a screen height 15 metre, 50 feet and you have a climb angle gamma. So it is from simple trigonometry And you can get gamma as $\gamma = \frac{T-D}{W}$, that is it.

Student: Sir.

Professor: Yes.

Student: Is not the screen height varying from place to place?

Professor: No, no, no screen height is defined by the regulatory body. You have 50 feet and 35 feet, for landing it is 35 feet and again for military aircraft and transport aircraft there are different numbers but it is 50 feet. It is a fix number, it is not a function of the airport. No, it is a regulatory requirement that you should clear 50 feet obstacle, ok so the requirement is same for all, so if you sum up these three times and sums you will be able to get the takeoff distance and time, ok.

Alright, so let us see what parameters influence the takeoff run, so the major portion is ground run unless you have a situation of engine failure or problem, correct. So ground run will decrease, takeoff run will decrease. So if we focus on ground run only because its a major part for normal takeoff and if we assume that the takeoff speed V1 is 10 percent higher not 15 percent, these number also varies, for defence aircraft it is 10 percent for civil it is 15 percent ok specified by the regulatory body.

So if you recall that $V_s = \sqrt{\frac{2W}{\rho S C_{L,max}}}$ so therefore S1 is the function of these parameter so you can see its very straight forward now, the S on the bottom I have taken up to put as W/S and one W I am keeping it in the denominator so I get ${}^{T}/_{W}$, ${}^{D}/_{W}$ and $1 - {}^{L}/_{W}$.

So in other words, ground roll increases as the wing loading increases. So one very important parameter is keep your wing loading low if you want to have a shorter takeoff ground run. In fact, when you do design, not as part of this course but when you do learn design, you will find there is going to be a requirement or a tendency to keep the wing loading low from low takeoff requirements, ok

Cl max if it is high, ground run will be low because it comes in denominator that is why we put flaps during takeoff and density, ground roll will increase as the wing density decreases, that is why at a hotter airport or at a higher airport where density is low and if you have hot plus high condition.

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$$S_1 = \frac{1.21(W/S)}{g\rho C_{L,max}\left[(T/W)-(D/W)-\mu(1-L/W)\right]_{avg}}$$

Can you name a place where you have hot plus high in India, high altitude but hot. So Leh airport is an example. During summer, Leh airport is one of the most difficult airports to operate because of the hot and high conditions. In the US people sight Denver as an example of an airport, which is hot and high, ok.

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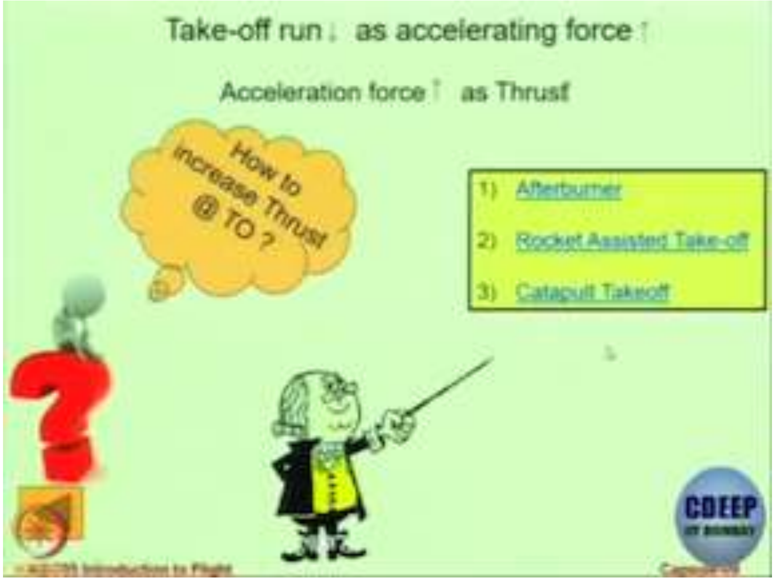

Take-off run ↓ as accelerating force ↑

Acceleration force ↑ as Thrust ↑

1) Afterburner
2) Rocket Assisted Take-off
3) Catapult Takeoff

So takeoff run also reduces as the accelerating force increases, so this is a very interesting thing, basically the faster you accelerate that means $T - D - \mu W$. So how do you increase thrust at takeoff, there are many ways of doing it, ok. The first way is using afterburners. Afterburner you are familiar what it is, I will just show you one nice video.

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You can see the afterburner, normally you do not see the large flame behind the aircraft, the aircraft's length and length of the afterburner flame is almost the same as you can see. Such afterburner can also cause tremendous problem to the runway, over a period of time the runway will start melting. We have experienced these problems in HAL when we worked on military aircraft, we had to relay the concrete because of the burning away, ok. So some aircraft take off with afterburner routinely.

One more way of doing it is called as JATO or RATO, Rocket assisted takeoff or Jet assisted takeoff. So this is a very interesting mechanism and you can see it in some military aircraft.

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So this is C130, the one on which you did the assignment, you see it has been fitted with rockets. As we show you C130 Demonstrates the jet assisted takeoff for JATO. Ok so this is one way. This is also possible on MiG 21 if needed, they have JATO facility or RATO facility as we used to call it.

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And then on the ships we routinely see just a catapult to launch a series of F18 fighter plane. Each catapult has enough muscle to provide for kilometers.

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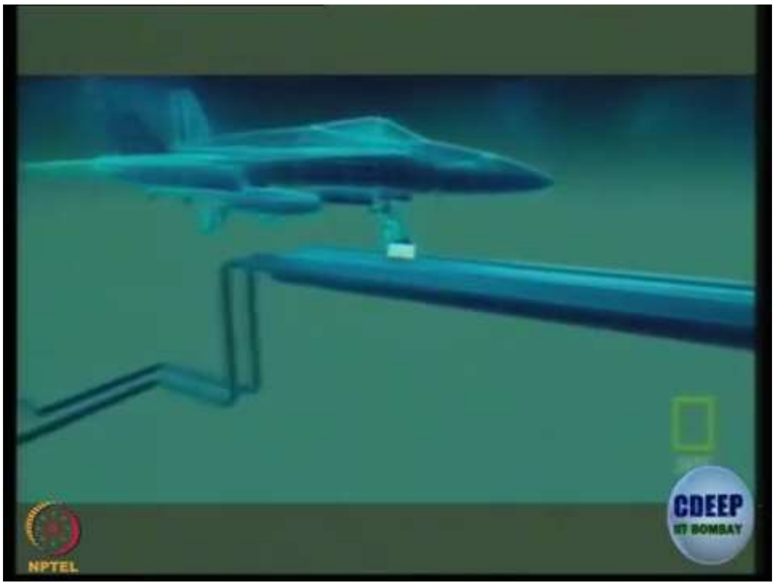
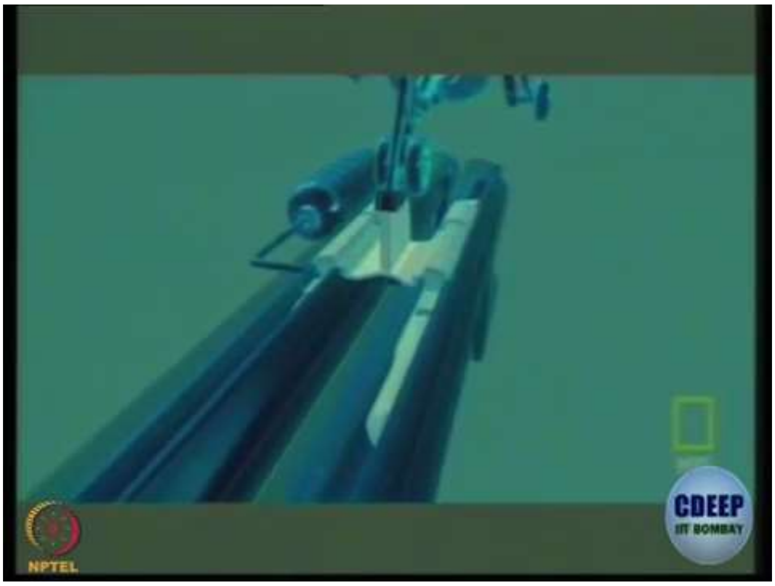
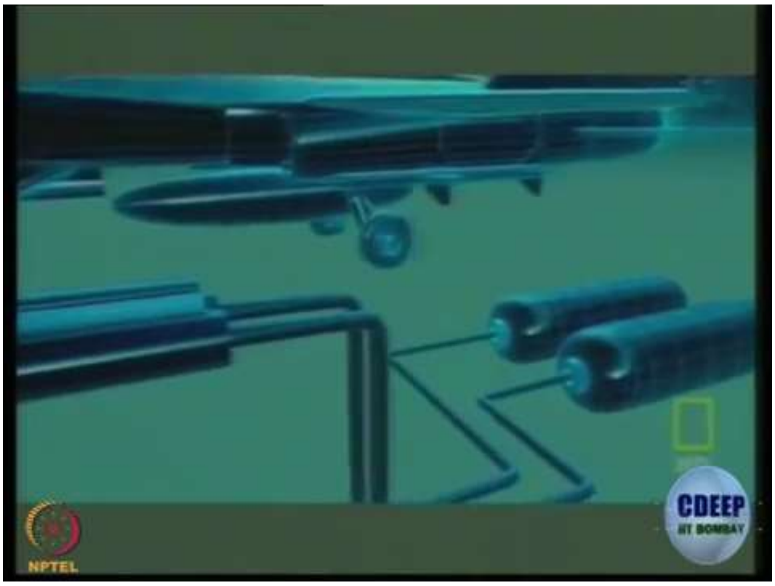




The secret of its power lies hidden beneath the tank, instead of complicated pulleys and wires the Limits has a pair of cylinders so on below runway. Inside these cylinders are pistons, pistons connects to planes through slots at top of the cylinder. (Refer Slide Time: 24:05)



They fill the cylinders with pressurize steam which shoots the pistons and the plane forward.

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To prevent the steam escaping they fit two strips of flexible metal that act like zippers and reseal the slots as the piston pass through, ok, so that is the catapult. So these are the typical ways by which we can increase the thrust.

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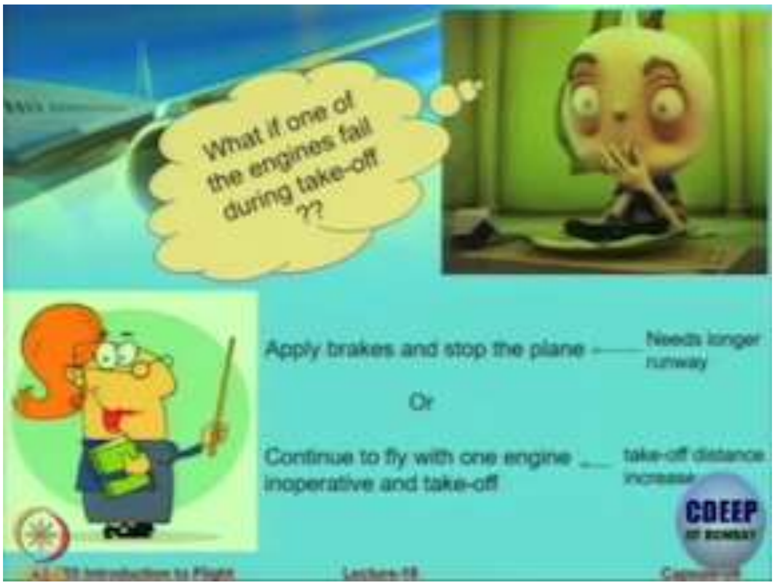

Apply brakes and stop the plane — Needs longer runway

Or

Continue to fly with one engine inoperative and take-off — take-off distance increase

Ok, now this is a situation when you have one engine failure during takeoff, so, yes you can apply brakes or you can continue to fly. So now we have to understand that there has to be a balance in these two. So obviously before V1 you will apply option number 1, after V1 you will apply option number 2.

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The speed of aircraft in this condition is called Decision Speed

$(s_{stop})_{decision\ speed} = (s_{stop})_{one\ engine\ failure}$

That decision speed is V1, interestingly at V1 the accelerate stop distance will be equal to the total distance needed from the start to reach the obstacle height, so that is why V1 is called as decision speed and this distance on the ground, total distance is called as the balanced field length, BFL.

So do you understand the balance here? The balance is that either you go for accelerate at V1, stop or you go for takeoff at V1, continue takeoff with one engine less, so you have lower thrust, so at a longer distance you will clear the obstacle height, you will clear it but at a longer distance. The speed V1 is such that these two distances are same.

So the definition of balanced field length is that distance from the point where the aircraft starts rolling to the point where either it comes to an accelerate stop distance or it clears the obstacle height, when the engine failure occurs at decision speed and these two are the same, that is the balanced field length. Ok.

So there are many simple formulae available in literature for calculating balanced field lengths but these are all numbers, I will not spend too much time on that. Also remember that when you fly near the ground then the vortex system on the wings is affected by the presence of the ground. So the strength of the wing tip vortex decreases because the wing tip vortex is killed by the ground, it is a upward push. So the wing tip vortex reduces. So therefore induced drag is reduced and therefore you will have some kind of a improvement.

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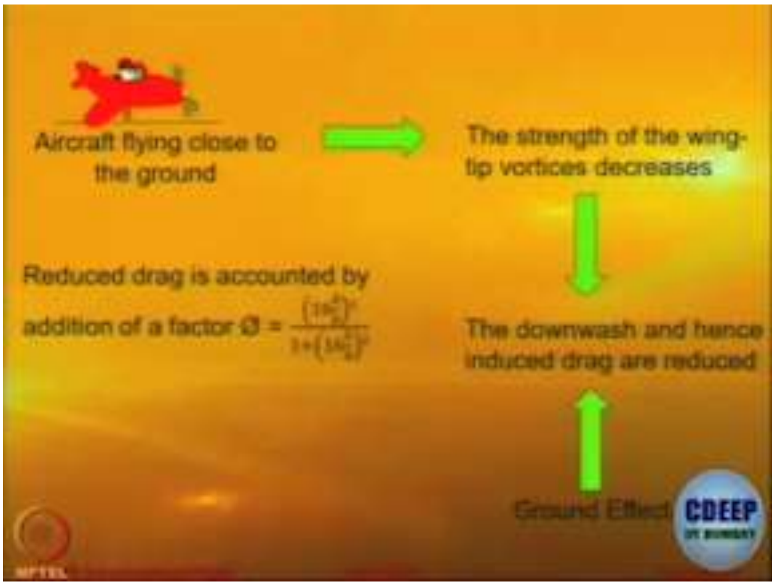

Aircraft flying close to the ground

The strength of the wing-tip vortices decreases

The downwash and hence induced drag are reduced

Ground Effect

Reduced drag is accounted by addition of a factor $\varnothing = \frac{\left(16\frac{h}{b}\right)^2}{1+\left(16\frac{h}{b}\right)^2}$

So the landing distance will have an issue because in landing you are being cushioned but in takeoff you are benefitted. So however the effect of ground wash, ground effects actually depends on how much high you are from the ground with respect to the wing span, so that is called as the factor phi, H over B, H is the height above the ground, B is the total wing span.

So normally it is said that when H is equal to B, that means at a height which is equal to one wingspan above the ground above that ground effect starts becoming almost 0. So you can assume to be out of the ground effect, below that height you have a factor Phi and the drag is reduced and therefore the landing the takeoff will be improved