Jet Aircraft Propulsion

Prof. Bhaskar Roy
Prof. A M Pradeep
Department of Aerospace Engineering
Indian Institute of Technology, Bombay

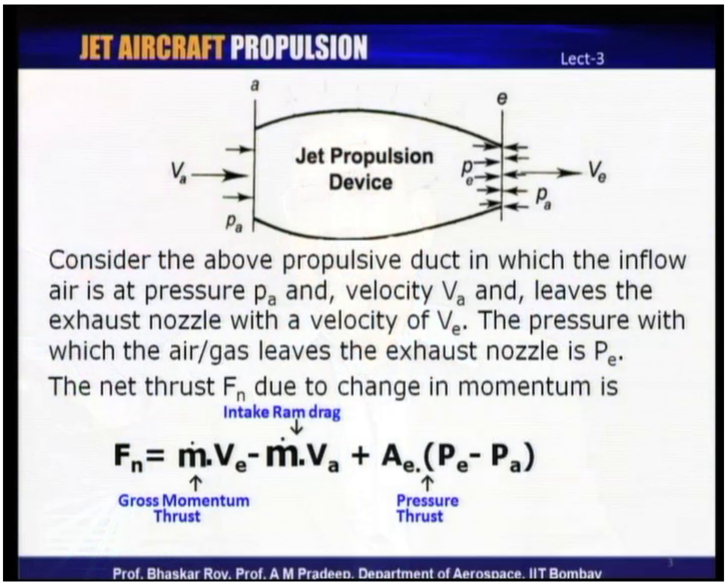
Lecture No. #03
Jet Engine Basic Performance Parameters

We are talking about jet engines and how the jet engine thrust is created. Now, jet engine as we know is normally used for creation of thrust for flying of aircraft. For different kinds of aircrafts, different ways of creation of thrust is often required. Having today's lecture, we will have a look at how this different kinds of thrust are created by slightly different variance of jet engine and we will have a look at how these thrusts are actually measured or quantified. Now, jet engine thrust is often a result of change of momentum as we have seen due to the Newton's laws of motion, most specifically the third law.

Now, that is a very summary way of understanding and putting how the thrust is actually created. The actual creation of thrust is often or little more involved and jet engine is a composition of machines. It itself is a machine by on its own. It is a mechanical machine, it is a thermodynamic machine, it is an aerodynamic machine and we will look at all three aspects of this machinery in the course of this lecture series.

In today's class, we will take a look at basically its mechanical composition and how mechanically it creates thrust. Later on in the course of this lecture series, we will be looking at them from thermodynamic point of view and later on we will be looking at them from aerodynamic point of view. So far as the components are all as I said thermodynamic entities as well as aerodynamic machines, let us take a look at how fundamentally the jet engine thrust are indeed created.

(Refer Slide Time: 02:50)



JET AIRCRAFT PROPULSION Lect-3

Consider the above propulsive duct in which the inflow air is at pressure p_a and, velocity V_a and, leaves the exhaust nozzle with a velocity of V_e. The pressure with which the air/gas leaves the exhaust nozzle is P_e.

The net thrust F_n due to change in momentum is

$$F_n = \underset{\substack{\uparrow \\ \text{Gross Momentum} \\ \text{Thrust}}}{\dot{m}}.V_e - \overset{\substack{\text{Intake Ram drag} \\ \downarrow}}{\dot{m}}.V_a + A_{e.}\underset{\substack{\uparrow \\ \text{Pressure} \\ \text{Thrust}}}{(}P_e - P_a)$$

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

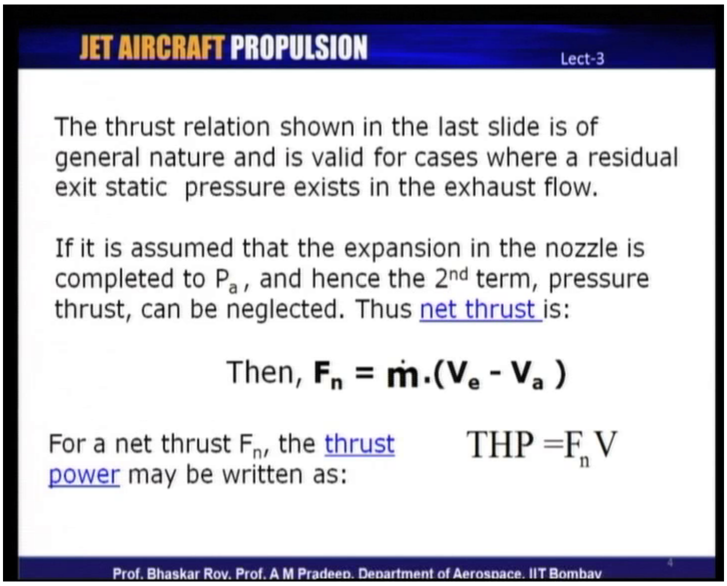
If you take a jet propulsion device and look at its fundamental thrust creating capability our understanding is that a certain amount of flow goes into the propulsion device. Let us say with a velocity V a coming from the atmosphere and we have discussed that basically, the jet propulsion device uses atmospheric air to do the work and create thrust and through the propulsion device, this air is accelerated and is exhausted with a velocity V e and may be a pressure P e which could be slightly different from atmospheric or ambient pressure P a. If that is the case, if that is what we can accomplish, then we can get a net thrust which we can write down simply as F substitute n equal to m dot into V e. Now, that is the gross momentum thrust that you get from the exhaust of the engine as a reaction to the jet exhaust.

Now, this is what you get as far as Newton’s third law. So, the first term is essentially a direct result of the Newton’s third law. The second term which is a negative term is m dot V a. Now, m dot is of course is the mass flow through the engine and that is the amount of air that is going inside the device and same amount of mass flow is coming out at the exit from the device. So, we assume for the time being that the entry mass flow and the exhaust mass flow are equal and same. We shall see later on that. They may not be exactly same. They may be slightly different, but we will come to that later on in the course of this lecture series, right. Now, let us say that the two mass flows are same. So, the second term is m dot into V a.

Now, this is the momentum with which the flow is going in and it is hitting the intake or inlet of the jet propulsion device. So, this is quite often referred to as intake ram drag. So, that is the momentum with which the air mass actually hits the propulsion device at the entry phase and it is then taken as a drag created by the incoming air and then, we have the third term which is an additive term which is the exit area A e multiplied by the pressure differential between the exiting air flow P e and the ambient pressure P a. Now, this differential pressure as we can see creates the third term and in the event when P e is exactly equal to P a and that is indeed quite possible. The third term would be zero which means there would be no pressure thrust and we will have only momentum thrust. That means we will have only two terms. The gross momentum thrust due to the Newton's third law is a reaction to the exhaust jet and the intake ram drag which is due to the intake of the flow coming into the propulsion device.

So, these are the fundamental features of creation of a thrust and the composition of all three together is often referred to as net thrust. For the moment, we will write it simply as F n will continue to probably refer to thrust in terms of f as we go along in this lecture series. Now, this creation of thrust as captured in this equation is a summary way of figuring out what the thrust could possibly be and a reasonably accurate estimation of the thrust.

(Refer Slide Time: 07:10)



JET AIRCRAFT PROPULSION Lect-3

The thrust relation shown in the last slide is of general nature and is valid for cases where a residual exit static pressure exists in the exhaust flow.

If it is assumed that the expansion in the nozzle is completed to P_a, and hence the 2nd term, pressure thrust, can be neglected. Thus net thrust is:

Then, $\mathbf{F_n = \dot{m}.(V_e - V_a)}$

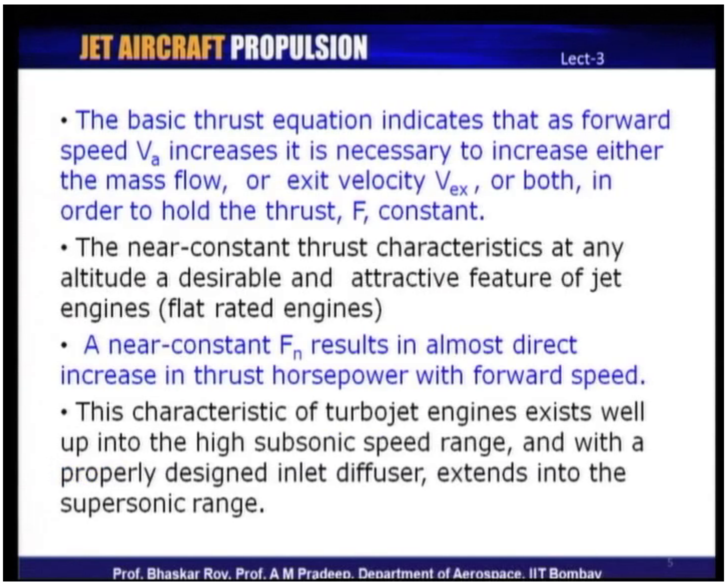
For a net thrust F_n, the thrust power may be written as: $\mathrm{THP} = F_n V$

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay 4

This thrust relation is what we call of a general nature normally valid. As I mentioned, when there is a residual exit static pressure which as I mentioned sometimes may not be there, which means the P e could be equal to P a in which gives the third term would be zero and as a result of which if the third term is zero, the net thrust would be simply m dot into V e minus V a. That is the velocity change across the propulsion device assuming for the moment that the mass flow that is going in is the same mass flow that is going out of the propulsion device.

So, this is a simple straight forward momentum thrust created by the propulsion device. Corresponding thrust can be also shown in terms of thrust power and that is simply written as THP is equal to F n into velocity with which the aircraft is moving. Now, that is the velocity with which the whole engine and the aircraft together are moving and that is the power that is being created by this propulsion device based on the thrust that is created by itself.

(Refer Slide Time: 08:47)



JET AIRCRAFT PROPULSION

Lect-3

- The basic thrust equation indicates that as forward speed V_a increases it is necessary to increase either the mass flow, or exit velocity V_{ex}, or both, in order to hold the thrust, F, constant.
- The near-constant thrust characteristics at any altitude a desirable and attractive feature of jet engines (flat rated engines)
- A near-constant F_n results in almost direct increase in thrust horsepower with forward speed.
- This characteristic of turbojet engines exists well up into the high subsonic speed range, and with a properly designed inlet diffuser, extends into the supersonic range.

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Now, the basic thrust equation that we have indicates that as the forward speed V a increases, it is necessary to increase either the mass flow, or the exit velocity or both in order to hold the thrust F constant. Now, let us look at the equation again. You have the mass flow as a contributing parameter to the thrust and you have the change of velocity as the contributing parameter to the thrust. For example, the aircraft starts flying at a higher velocity that is V a in which case the thrust is going to go down unless V e increases or unless m dot increases. So, which means you have to find ways or means of increasing either V e or increasing m dot to hold down to your thrust value, otherwise your thrust is going to start going down.

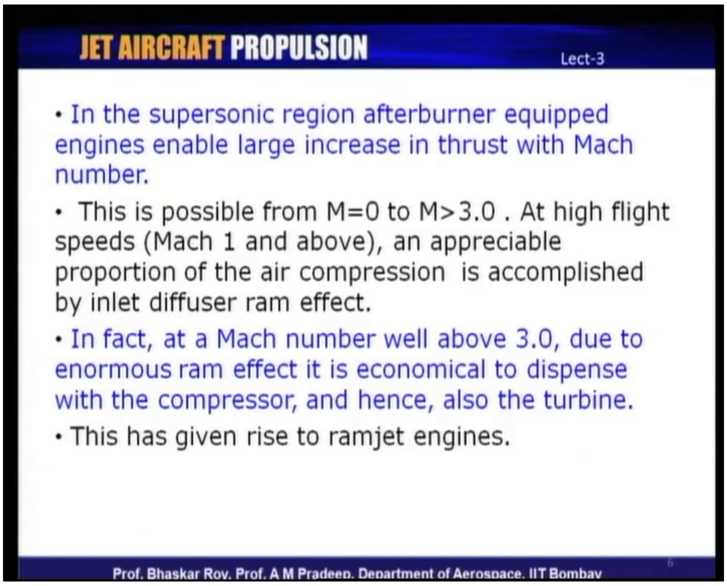
Now, this is pretty much a known phenomenon and a known problem as comes out from this simple momentum equation in case of certain kinds of jet engine as we shall see later on as we go along. For example, scramjet engine for hypersonic aircraft, the value of different between V e and V a could be so small that under certain operating conditions, it is indeed possible that V a actually would be higher than V e which means a thrust creation would be negative. Now, that is a realistic possibility under certain operating conditions of certain kinds of jet engines, for example scramjets.

So, it is a realistic situation which comes out of this simple momentum equation that you have to keep an eye on the three parameters. Primarily, the mass flow, the entry velocity V a, which is dependent on the aircraft flight velocity and the exit velocity V e which is indeed what is created by the propulsion device. So, propulsion device need to be tuned to create a certain amount of thrust as required and these are the three parameters. One needs to keep aware of during the entire flight. During the entire flight process, all the three parameters need to be kept an eye on or to be under control.

Now, many of the jet engines are designed to create near constant thrust characteristic often referred to as flat rated characteristics at any particular altitude, which means at any particular altitude, if the aircraft is flying, the thrust created would be more or less constant and in which case, various aircraft maneuvers can then be created or then can be designed for the aircraft knowing that the propulsion device is going to give us almost continuous constant thrust during the flight at that particular altitude. So, quite often engines are designed to create near constant thrust characteristics at any altitude.

Now, of course, as we have seen from the THP definition that if the thrust is held constant and if your flight velocity is indeed increased, flight speed is increased, the thrust power is not good now going to up. So, it will result in higher and higher thrust power with the forward speed. Now, this characteristic of turbojet engine is quite often available at high subsonic speed ranges and with a properly designed inlet diffuser extends well into the supersonic range. Now, we will be talking about the thermodynamics and aerodynamics or supersonic engines which are meant for supersonic aircraft. So, when an aircraft is flying supersonic, the intakes need to be designed accordingly and some of those things we will be discussing later on in the course of this lecture, but at this moment, let us just try to understand that under certain operating a flight conditions, the engine operating condition needs to be matched in such a manner that the thrust creation is in tune with the requirement of the flight of the aircraft. One of the simple ways of creating thrust is to create a constant or near constant thrust at any given altitude.

(Refer Slide Time: 13:59)



JET AIRCRAFT PROPULSION

Lect-3

- In the supersonic region afterburner equipped engines enable large increase in thrust with Mach number.
- This is possible from M=0 to M>3.0 . At high flight speeds (Mach 1 and above), an appreciable proportion of the air compression is accomplished by inlet diffuser ram effect.
- In fact, at a Mach number well above 3.0, due to enormous ram effect it is economical to dispense with the compressor, and hence, also the turbine.
- This has given rise to ramjet engines.

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

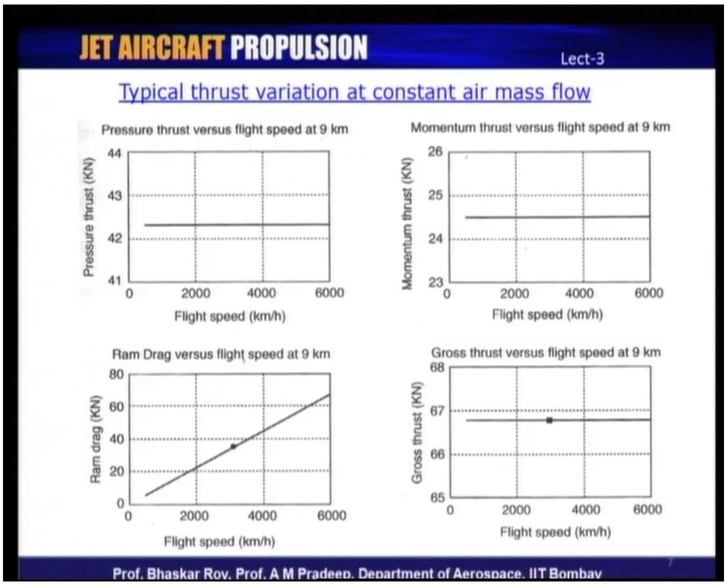
6

In the supersonic region, quite often the jet engines are equipped with afterburners. Now, these afterburners straight away give you more thrust and now as we see, as we have just seen if the velocity of the aircraft actual is increased, that is V a is increased, you need to increase V e. The exhaust velocity and afterburner is one simple straight forward way of increasing V e and this is possible when the mach number is increased from 0 to up to about mach 3 and at such high flight speeds, that is mach 1 and above, that is supersonic mach numbers and appreciable proportion of the air compression is accomplished in the inlet diffuser. We shall see later on that inlet is an aerodynamic entity. It is an aerodynamic component which essentially converts kinetic energy to pressure and had a very high supersonic mach number. If this can be done efficiently, how it can be run efficiently, we will discuss later on in this course.

If it can be done efficiently, then you can create sufficient amount of pressure and this pressure then can be utilized later on in the nozzle to create a high velocity jet. So, to create a high velocity jet, you need a certain amount of residual pressure going into the nozzle and some of this pressurization can indeed be done right in the intake system itself as and when the air is coming into the propulsion device. In fact, at a mach number well above 3, due to the very high kinetic energy conversion often referred to simply as ram effect. It is quite possible to even dispense with the compressors of a typical jet engine and hence, also the turbine.

Now, some of these things we will be discussing in more detail. As I mentioned both thermodynamic engines as well as later on as aerodynamic machines and these machines are or jet engines are simply called ram jet engines and as I mentioned we shall be discussing ram jet engines and its variance later on, both as thermodynamic entities in terms of their thermodynamic cycle analysis and also later on as aerodynamic or gas dynamic machines.

(Refer Slide Time: 16:45)



JET AIRCRAFT PROPULSION Lect-3

Typical thrust variation at constant air mass flow

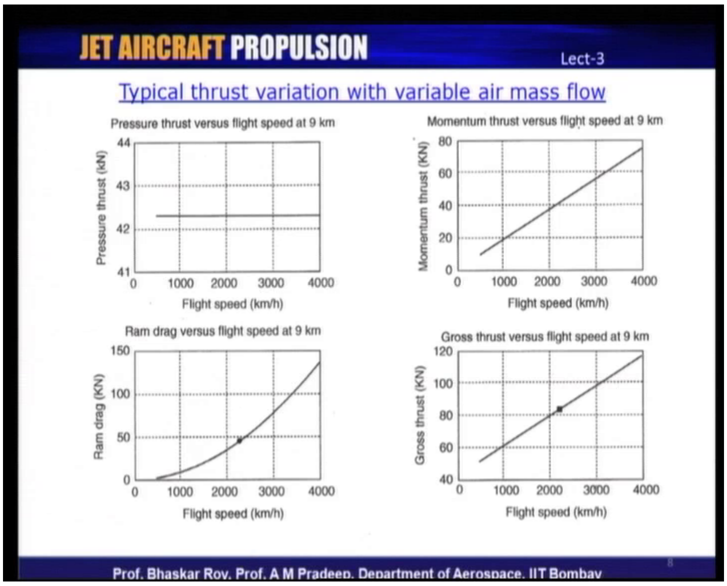
Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Let us take a look at simple thrust variation characteristics of a simple jet engine that we looked at. Let us say, a constant air mass flow. Supposing the air mass flow through the engine is held constant, let us say by some design of the intake. So, at a particular altitude, in this case we are looking at a flight at an altitude of 9 kilometers which is quite often a normal altitude at which many of the jet engines actually fly with aircraft.

If the constant aircraft mass flow is held constant, the pressure thrust as we looked at is lightly to be constant. There is no reason why it should change with the flight speed. The momentum thrust versus the flight speed tells us that it is likely to be constant. The ram drag as we saw the first second term, that is due to the air intake keeps going up. If the air mass flow is constant as a flight speed is going up, V a is going up, m dot is constant. So, m dot into V a is going to go on increasing with the flight speed.

The gross thrust that is the first term is held constant, that is V e is constant, m dot is constant. So, there is no reason why the first term that is the gross term due to the Newton’s third law should change. So, this is how the three components that we looked at actually would behave if the air mass flow is held constant, but holding the air mass flow constant requires a certain amount of design of the intake system which is often not quite a done thing.

(Refer Slide Time: 18:52)



JET AIRCRAFT PROPULSION Lect-3

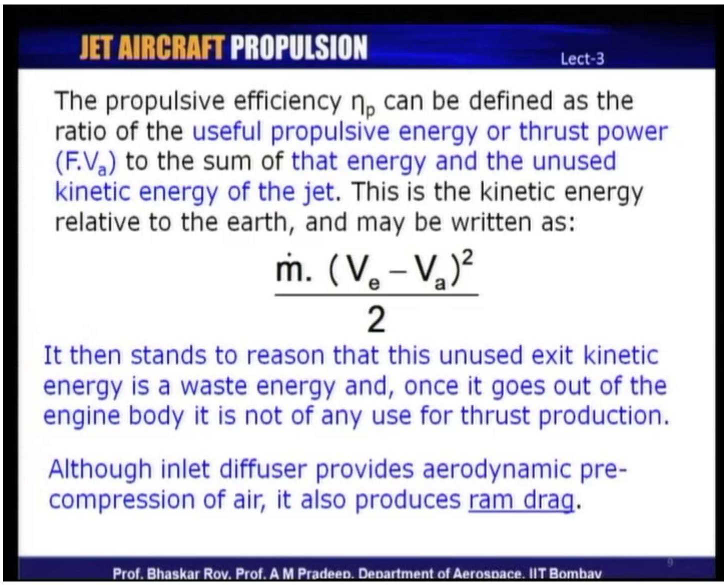
Typical thrust variation with variable air mass flow

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

So, quite often what is done thing is the air mass flow actually varies with the flight speed and if it does vary, let us look at how the various components would vary. The pressure thrust would actually again be held constant. There is no reason why that should vary.

However, now the momentum thrust would increase with the flight speed because the ram drag now has a non-linear characteristic. It varies non-linearly with the change of air mass flow and with the change of flight speed. As both the components are now changing, the gross thrust now would also vary because air mass flow is now varying. So, the first component would also increase with the flight speed. So, as we can see depending on how the air mass flow is controlled through the intake system, the thrust characteristic of the engine would actually vary. In fact, in some of the cases, some of the jet engines may be possible to have variable geometry intake system by which the air mass flow can be metered or varied. However, the more used method of varying the air mass flow of course is using the variable geometry exhaust nozzle and almost all the jet engines that are flying today, do have variable geometry exhaust nozzle through which the air mass flow can be metered or controlled in a flying engine.

(Refer Slide Time: 20:43)



JET AIRCRAFT PROPULSION

Lect-3

The propulsive efficiency η_p can be defined as the ratio of the useful propulsive energy or thrust power ($F.V_a$) to the sum of that energy and the unused kinetic energy of the jet. This is the kinetic energy relative to the earth, and may be written as:

$$\frac{\dot{m}.\,(V_e - V_a)^2}{2}$$

It then stands to reason that this unused exit kinetic energy is a waste energy and, once it goes out of the engine body it is not of any use for thrust production.

Although inlet diffuser provides aerodynamic pre-compression of air, it also produces ram drag.

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

9

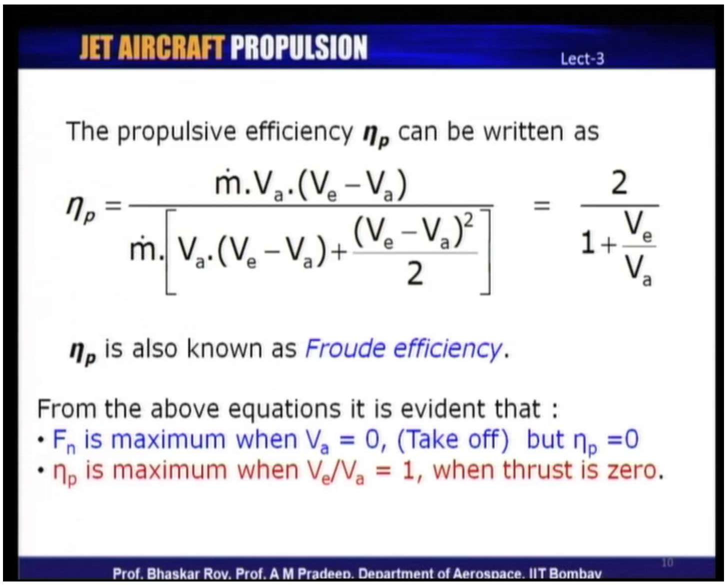
Let us now take a look at some of the other parameters that affect or influence the behavior of typical jet engines. Now, the propulsive efficiency which is often a term that can be defined as a ratio of the useful propulsive energy or thrust power which we just had a look at and that as a ratio of the energy and the unused kinetic energy of the jet. Now, the energy that is available for creation of thrust power that is the energy, that is indeed created into the thrust power and the unused kinetic energy of the jet, some of the two actually is the energy that is available for propulsive purposes.

Now, the kinetic energy that is going out relative to the earth may be written as m dot into V e minus V a whole thing to the power square to the power 2 divided by 2. Now, this is the kinetic energy with which the energy is released from the propulsive device and this kinetic energy goes out of the propulsive device and has is of no use to us anymore once a thrust has been generated. So, it is called unused kinetic energy of the jet and hence, one can say that this is a waste energy. It goes out of the energy of the engine body. Now, this is something which we will be concerned with and we will be talking about it in terms of a engine performance in terms of cycle performance and later on in terms of nozzle performance in different ways and there are many facets of looking at some of these parameters and we will be looking at these parameters in various ways in the course of this lecture series.

Now, let us remember that the inlet diffuser with which, through which the flow is coming in it provides aerodynamic pre-compression as we have discussed just little earlier and it also produces the ram drag as we have seen. So, the diffuser that we had a look at had both utility values in terms of producing a certain amount of compression. It also produces a negative aspect that is what we call the ram drag.

So, the jet exhaust has a certain positive thing that it produces a reaction thrust. It also produces an unused kinetic energy of the exhaust jet. The intake similarly produces a pre-compression of the air, but it also produces certain amount of ram drag which is a negative component as far as the thrust creation is concerned.

(Refer Slide Time: 23:53)



JET AIRCRAFT PROPULSION Lect-3

The propulsive efficiency η_p can be written as

$$\eta_p = \frac{\dot{m}.V_a.(V_e - V_a)}{\dot{m}\left[V_a.(V_e - V_a) + \frac{(V_e - V_a)^2}{2}\right]} = \frac{2}{1 + \frac{V_e}{V_a}}$$

η_p is also known as *Froude efficiency*.

From the above equations it is evident that :

- F_n is maximum when $V_a = 0$, (Take off) but $\eta_p = 0$
- η_p is maximum when $V_e/V_a = 1$, when thrust is zero.

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay 10

Now, we can look at what the propulsive efficiency of this propulsion device could be written down as and as we have written, just talked about in terms of words, we can write it in the form of equation. Now, the numerator indeed is the thrust that is being created, thrust power that is being created that is thrust into the velocity with which the aircraft engine combined is moving in air. So, that is the relative velocity between the aircraft engine and the air, the atmospheric air which let us say for the time being is still air and the denominator is that thrust power plus the kinetic energy which we just mentioned which is going out as waste.

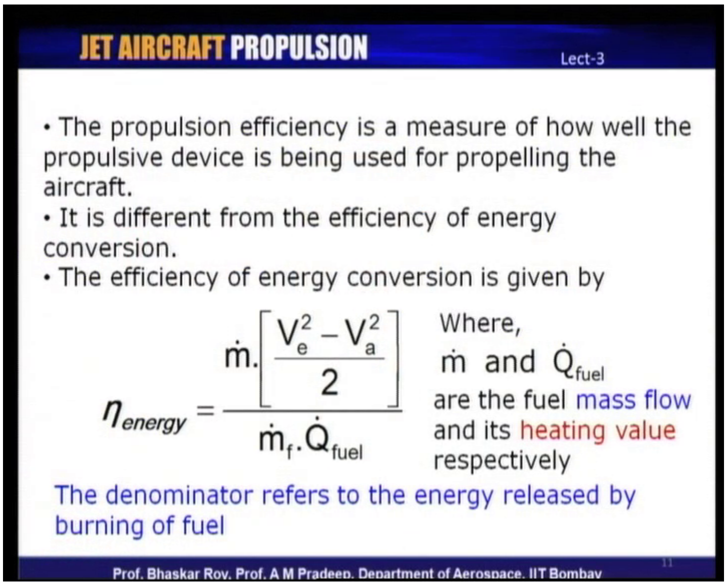
Now, if you write that down as defined in the last slide, it all boils down to a very simple relation, that is 2 divided by 1 plus V e by V a. Now, this relation is also known as a Froude's efficiency. Technically, it reaches the propulsive efficiency of the propulsive device. It is developed by a gentleman called Froude little more than 100 years back and it is often also referred to as Froude's efficiency. What we can see from this relation and this is something we will be talking about it more and more as we go into various variance of jet engine and this has to be looked into in many different ways.

We shall be doing it over the course of the lectures, but let take a quick look at what it means simply, very simply. It is evident that the net thrust is maximum when V a is 0. That means, aircraft is actually on the take off. Just before the take off, it is static and it is not moving. It is on the top of the take off run (refer time: 26:00) and V a is 0 and that is when the F n is going to be maximum. The thrust is maximum, but if you look at the propulsive efficiency, now your propulsive efficiency is 0 according to this theory that we are looking at.

On the other hand, propulsive efficiency is maximum when the ratio of V e by V a is equal to 1. So, this theory tells us that V e by V a is equal to one propulsive efficiency is maximum, that is 100 percent, but that is the point when the thrust is going to be 0. If the thrust is simply equal to V e minus V a, and the thrust is going to be 0, so we have to absolutely opposite contradictory situations. That means, when the thrust is maximum theoretically, the propulsive efficiency is 0 and when the propulsive efficiency is possibly maximum, the thrust is going to be 0. So, it is obvious that these theoretical possibilities are the two extremes. Some of which may not actually happen, but the engine would have to operate between these two extremes and somehow, we have to configure our engine to keep this in mind that when the two velocities keep changing from certain value to V e by V a equal to 1 or a certain value in which V a is indeed 0, the propulsive efficiency and the thrust creation pull the whole propulsive device in two opposite direction.

So, we have to just simply keep it in mind that theory tells us certain contradictory situation can arise under two different or two opposite operating conditions. This is of course what the theory tells us. The propulsion efficiency as we know is a measure of how well the propulsive device is being used.

(Refer Slide Time: 28:10)



JET AIRCRAFT PROPULSION

Lect-3

- The propulsion efficiency is a measure of how well the propulsive device is being used for propelling the aircraft.
- It is different from the efficiency of energy conversion.
- The efficiency of energy conversion is given by

$$\eta_{energy} = \frac{\dot{m}.\left[\frac{V_e^2 - V_a^2}{2}\right]}{\dot{m}_f.\dot{Q}_{fuel}}$$

Where, $\dot{m}$ and $\dot{Q}_{fuel}$ are the fuel mass flow and its heating value respectively

The denominator refers to the energy released by burning of fuel

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

11

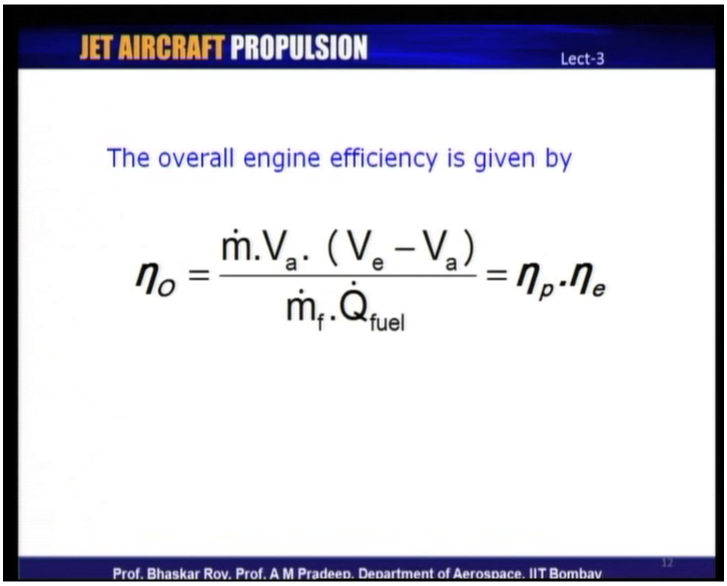
The propulsive efficiency that we are looking at that we have just defined is actually comparable let us say to a propeller efficiency, where propeller is the propulsive device and when we have a propeller driven engine, the propulsive efficiency of a typical jet engine would be comparable to the propeller efficiency of the propeller driven engine or propeller driven thrust making device.

So, when we compare the propulsive efficiency of a typical jet engine on that of a typical propeller driven thrust device, we are comparing the jet propulsive efficiency with the propulsive efficiency of the propeller. We have to remember that the efficiency as we have defined now as a propulsive efficiency is different from other efficiencies that we will be defining in the course of this lecture series and it is different to begin with from the energy conversion efficiency. There are many efficiency that would be coming up in the course of thermodynamics. There efficiency is like thermal efficiency, but at the moment, let us look at what is simply often known as efficiency of energy conversion. This is simply a ratio of the energy that is put in by burning the fuel and the energy that is created for creation of thrust. Now, energy that is created for creation of thrust as we have just seen, not whole of it is utilized by the engine for thrust creation. Only part of it is utilized.

So, this is now a efficiency of energy conversion where we are just looking at how much of the fuel mass burnt energy is available for energy in terms of available for thrust creation. So, the numerator here is m dot into V e square minus V a square divided by 2, that is the energy that is available for thrust creation and the denominator is the energy that is been simply made available by burning of the fuel and released by the chemical energy that is released by burning of the fuel. The denominator is dependent on the mass flow of the fuel and the heating value of the fuel. So, you have to choose your fuel properly, so that it has highest possibility in value without creating any other problems and the fuel mass flow of course gives you the amount of energy that can be released.

As we go along, we shall see later on that you simply put in more fuel, you can get more and more energy available and hence, more and more energy can be made available for thrust creation, but you have earning more fuel. So, that may not be the most fuel efficient way of getting more thrust. So, this simply tells us that if you burn more fuel, you can indeed get more available energy for thrust creation. How you create the thrust that is a second matter. That is another matter, but if you burn more fuel, you can get more energy for thrust creation and this is indeed what is quite often done. For example, if you have a reheat engine or afterburning engine in which simply more fuel is pumped in and that more fuel simply gives us more energy for creation of thrust, how that is utilized efficiently. We shall see later on as we go along in this lecture series.

(Refer Slide Time: 32:09)



JET AIRCRAFT PROPULSION

Lect-3

The overall engine efficiency is given by

$$\eta_o = \frac{\dot{m}.V_a.\ (V_e - V_a)}{\dot{m}_f.\dot{Q}_{fuel}} = \eta_p.\eta_e$$

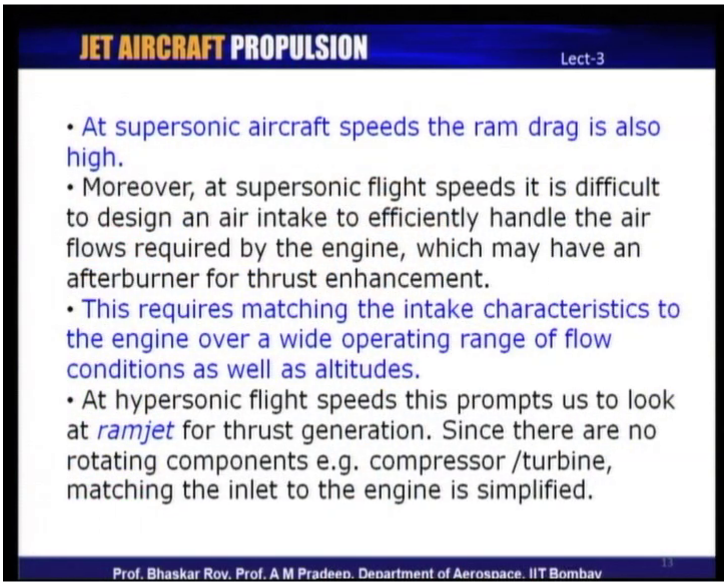
Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

So, the overall energy efficiency is quite often simply written down in terms of the thrust power that is created and the fuel energy that is been released by burning of the fuel. So, that is the overall engine efficiency. The efficiency of thrust creation as opposed to the energy available from the fuel burning and this simply comes out to be a product of the propulsive efficiency and the energy efficiency we just saw in the last two slides. So, the two earlier energy efficiencies, propulsive efficiency and the energy efficiency are together responsible for creating the overall engine efficiency and hence, we need to keep an eye on the propulsive efficiency and the energy efficiency, both of them. Over the course of these lecture series, we shall see how these two parameters are maximized to get higher and higher overall engine efficiency. There are methods, both thermodynamic and aerodynamic by which these two parameters can be improved or maximized under various operating conditions of the engine to get better and better overall engine efficiency and that is what we will be discussing over the course of this lecture, ok.

Now, we know that jet engines are used not only for flying aircraft in subsonic speeds. Today, many of the aircrafts, more specifically the military aircraft do fly at supersonic speeds. Now, at supersonic speeds, the incoming velocity is non supersonic. V a is now very high and hence, as we have discussed before the ram drag is also going to be very high. Now, it stands to reason that if you have very high intake velocity, you would need to create high exit velocity, something we have just thrust upon a little earlier. So, if you are flying at supersonic speed, then your entry velocity is high and your exit velocity will also have to be high and your ram drag is high.

So, to overcome that ram drag, you need to create more and more thrust. So, the first thing is you need to create air intake to take in the supersonic air that is coming in efficiently, so that your pre-compression that we talked about is done more and more efficiently. So, the ram drag, the penalty that you are paying for is suitably compensated by an efficient pre-compression. If you can create efficient pre-compression, later on it is very useful for you to create higher exhaust velocity. So, you need to create a very good intake system to create a very good pre-compression and we shall be discussing various aspects of intakes later on in the course of this lecture series.

(Refer Slide Time: 35:28)



JET AIRCRAFT PROPULSION Lect-3

- At supersonic aircraft speeds the ram drag is also high.
- Moreover, at supersonic flight speeds it is difficult to design an air intake to efficiently handle the air flows required by the engine, which may have an afterburner for thrust enhancement.
- This requires matching the intake characteristics to the engine over a wide operating range of flow conditions as well as altitudes.
- At hypersonic flight speeds this prompts us to look at *ramjet* for thrust generation. Since there are no rotating components e.g. compressor /turbine, matching the inlet to the engine is simplified.

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay 13

Now, if you can do that what it says is that you can then effort to have an afterburner. Now, that means that you would need to create a intake system in which the engine which operates under various operating conditions, under various mass flows as we have seen, the mass flow through the engine can be varied. An intake is one of the parameters, one of the components through which the mass flow can be metered. The more active component being the nozzle of course and if you do that, then you need to continuously match the intake performance with the engine and the aircraft combine and this is something that needs to be done on a continuous basis during the entire flight of the aircraft.

At hypersonic speeds, you have intake requirement that is of a even greater challenge and you need to create thrust generation at hypersonic speeds, where the intake velocity is of very high and you need to create exhaust velocity which is even higher and there are no rotating components. Now, this is of course a challenge which we shall be discussing in great detail as I mentioned both thermodynamically as well as aerodynamically or gas dynamically as we go along over this course.

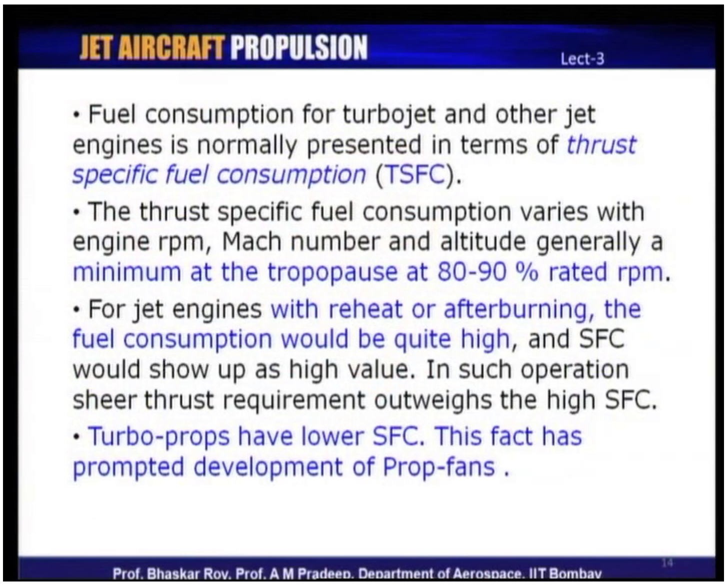
Now, the fuel consumption for turbojet and other jet engines is normally presented in terms of what is known as specific fuel consumption or more specifically for jet engines thrust specific fuel consumption. Now, we shall see as we go along that the thrust specific fuel consumption is actually are more utilized parameter or figure of merit for the efficiency of the engine. The efficiency parameters that we have defined are indeed used by the designers or theoreticians or for calculation purposes, but for operational purposes, for operators, the more useful parameter is the specific fuel consumption or thrust specific fuel consumption which directly keeps an eye on the fuel consumption of the engine during the various phases of the flight of the aircraft engine.

Now, thrust specific fuel consumption varies with the engine RPM. Now, we have rotating components as we have seen compressors turbines and the engine aircraft combine flys at various mach numbers, at various altitudes and quite often at its slight altitudes somewhere near very high altitude. It is generally operating at somewhere around 80 to 90 percent of its maximum or rated RPM. So, all those parameters are varying and you have to keep an eye on the thrust specific fuel consumption or TSFC. Now, when you have reheat or afterburning as we keep talking about and we shall see that you simply burn more fuel and obviously, the SFC goes up.

So, what it shows is that if you simply pump in more fuel, you get more thrust. You are getting more thrust at the expense of burning more fuel, so that it will show up in SFC. You will get more thrust, you will have more fuel burning and SFC is indeed going to go up. So, what you are doing is you desperately need thrust, you burn more fuel, you sacrifice SFC which is either said a measure of fuel efficiency of the engine, you sacrifice for that for the time being just to get some more thrust which you need desperately for flight requirement of the aircraft.

So, that is one way of getting more thrust simply by increasing the SFC.

(Refer Slide Time: 39:46)



JET AIRCRAFT **PROPULSION**

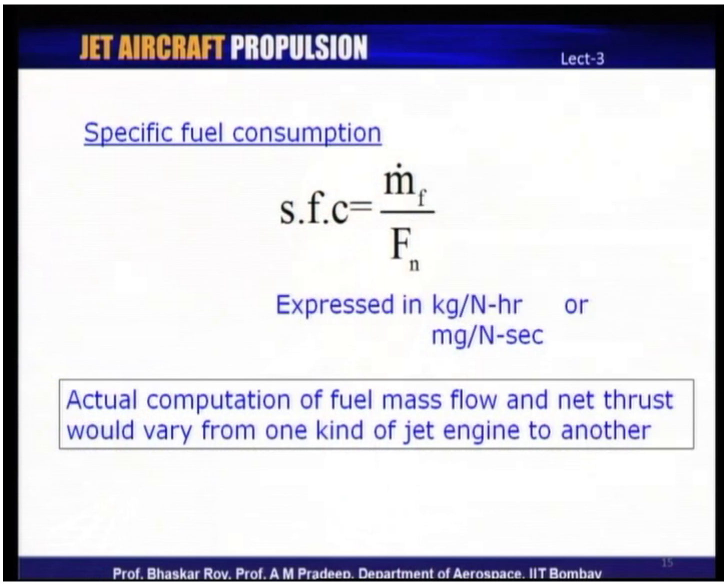
Lect-3

- Fuel consumption for turbojet and other jet engines is normally presented in terms of *thrust specific fuel consumption* (TSFC).
- The thrust specific fuel consumption varies with engine rpm, Mach number and altitude generally a minimum at the tropopause at 80-90 % rated rpm.
- For jet engines with reheat or afterburning, the fuel consumption would be quite high, and SFC would show up as high value. In such operation sheer thrust requirement outweighs the high SFC.
- Turbo-props have lower SFC. This fact has prompted development of Prop-fans .

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Now, the turbo-props have quite often lower SFC. As we have mentioned before, the propellers are indeed more efficient flying device and they often have lower SFC's and this is one of the reason, this is not of the main reason because of which propellers are now being weak configured in the form of prop-fans for creating new breed of jet engines and we will be looking into them later on which have higher SFC. So, SFC is a figure of merit. A very important parameter that is driving the development of new varieties of jet engines and it is been driving the development of jet engines over the last 30-40 years of the development of various kinds of jet engines.

(Refer Slide Time: 40:44)



JET AIRCRAFT PROPULSION

Lect-3

Specific fuel consumption

$$s.f.c = \frac{\dot{m}_f}{F_n}$$

Expressed in kg/N-hr or
mg/N-sec

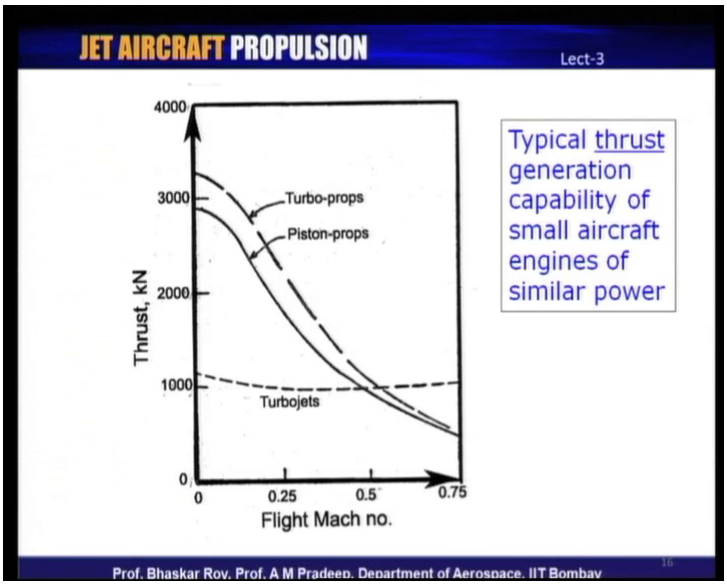
Actual computation of fuel mass flow and net thrust would vary from one kind of jet engine to another

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Simply put the specific fuel consumption is defined in terms of simply the mass flow that is of the fuel that is actually put into the engine divided by the net thrust. So, that is simply the s f c and it is often expressed in terms of in SI system. It is expressed in terms of kilograms per newton hour or milligrams per newton second to confirm to certain good looking numbers. Now, the actual computation of fuel mass flow and indeed s f c and of course net thrust would vary from one kind of jet engine to another and that we will be discussing later on in the next few lectures through your cycle analysis. Through your thermodynamic performances, we shall see how these parameters are indeed quantified for various variance of jet engine.

Let us take a quick look at how jet engines (()) in comparison to other kinds of aircraft repulsive devices.

(Refer Slide Time: 41:59)



JET AIRCRAFT PROPULSION

Lect-3

Typical thrust generation capability of small aircraft engines of similar power

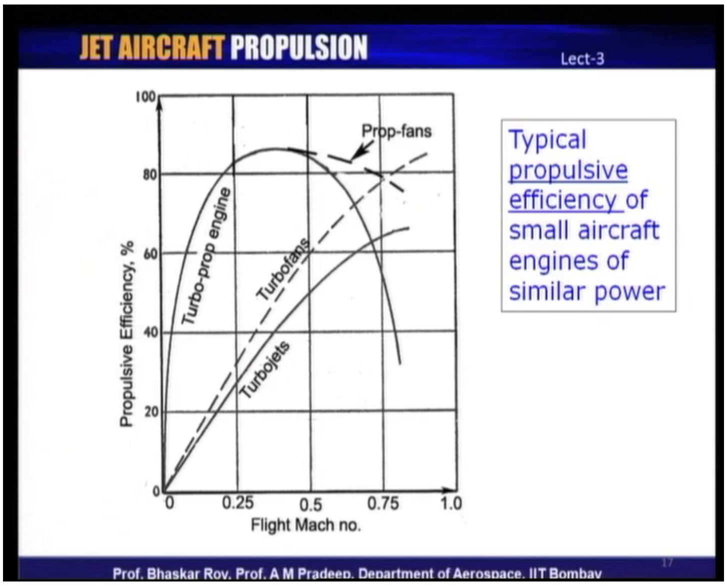
Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

16

Now, if you look at this, you will see that as we mentioned earlier jet engines by design quite often have what can be called or rather flat operating characteristic whereas, typically the propeller driven engines or propulsive devices have the thrust watt keep going down with flight mach number. One of the reasons is that the propeller efficiency starts going down and hence, a thrust created by it also goes down and there is certain flight mach number at which typically the jet engine start becoming more and more profitable for flight of aircraft.

So, there is a flight mach number below which it might be profitable to use propeller driven engines, but beyond that flight mach number, it may be profitable to look at various variance of turbojet engines or jet engines for powering aircraft flight.

(Refer Slide Time: 43:05)



JET AIRCRAFT PROPULSION

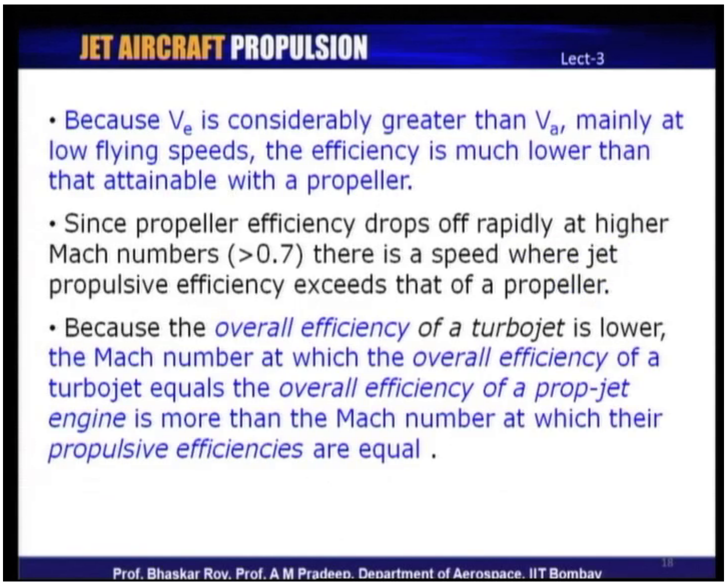
Lect-3

Typical propulsive efficiency of small aircraft engines of similar power

If you look at the propulsive efficiency which we have defined earlier, we shall see that the three variance that we looked at also have three different kinds of characteristics. The turbo prop engines as we see reach a peak of propulsive efficiency and then, it starts falling off. The modern prop-fans which I just mentioned give it a new lease of life or same and extend its capability to higher flight mach numbers. On the other hand, the turbojets and the turbo fans have increasing propulsive efficiency with mach number, flight mach number.

A certain flight mach number, they overtake the propeller driven engines and as I mentioned, they become more and more profitable and that profit actually shows up in the form of s f c. The turbo fan engines also have a certain characteristics and even they take over from the prop fans at certain higher flight mach number at which then the prop fans would probably need to give a way to pure turbo fans. So, these are some of the simple guidelines which are available. We will look into the details of some of these things and quantify these numbers as we go along with various variance of jet engine.

(Refer Slide Time: 44:39)



JET AIRCRAFT PROPULSION Lect-3

- Because V_e is considerably greater than V_a, mainly at low flying speeds, the efficiency is much lower than that attainable with a propeller.
- Since propeller efficiency drops off rapidly at higher Mach numbers (>0.7) there is a speed where jet propulsive efficiency exceeds that of a propeller.
- Because the *overall efficiency of a turbojet* is lower, the Mach number at which the *overall efficiency* of a turbojet equals the *overall efficiency of a prop-jet engine* is more than the Mach number at which their *propulsive efficiencies* are equal .

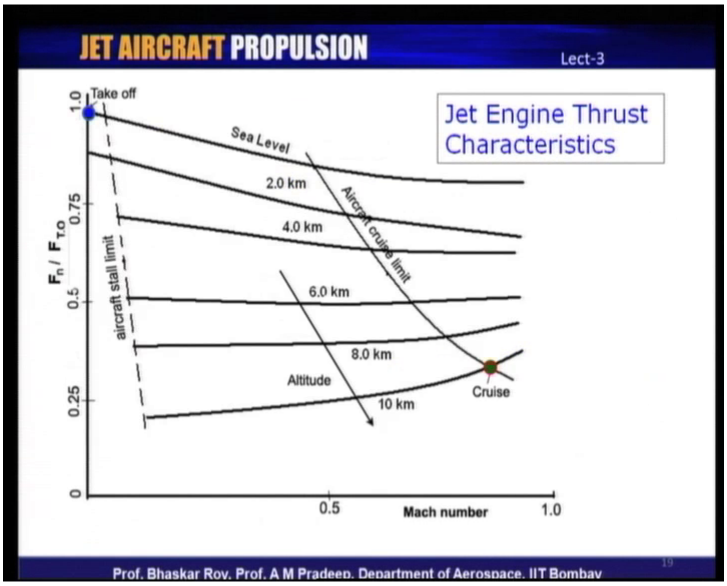
Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay 18

Now, since exhaust velocity V e is considerably higher than the incoming velocity V a and this is true mainly at low flying speeds. The efficiency is much lower than that attainable with a propeller. Now, this is the reason that V e is since it is considerably higher than V a, it entails that is a huge lot of waste energy that is going out and as a result of which the propulsive efficiency is low. When the aircraft fly's at a higher speed, the difference between V e and V a is considerably less. Theoretically, as we have seen, it is highest when V e is indeed equal to V a, but we always need to keep a positive value there and hence, if the increasing mass flow, they start giving reasonable amount of thrust for flying the aircraft and that is when the efficiency becomes higher than that of a propeller.

The other thing that happens is the propeller efficiency starts dropping somewhere around mach 0.5 by mach 0.7. They become really uncompetitive because somewhere over the propeller, the aerodynamics of the flow over the propeller go supersonic and the propeller start becoming less and less efficient and that is where the jet engine propulsive efficiency takes over from the propeller driven propulsive devices. All this tells us that the overall efficiency of a turbojet. Firstly, it is lower, but the mach number at which the overall efficiency of a turbojet equals that of a overall efficiency of a turboprop or a prop jet is normally more than the mach number at which their propulsive efficiencies are equal.

So, as we have seen the propulsive efficiency is different from overall efficiency. So, the mach number at which the two are equal at if the jet engine and propeller engine is different from propulsive efficiency point of view compared to that of overall efficiency point of view. So, it will vary from one kind of engine to another and exact values would need to be computed to find out where they become more and more profitable.

(Refer Slide Time: 47:13)



JET AIRCRAFT PROPULSION

Lect-3

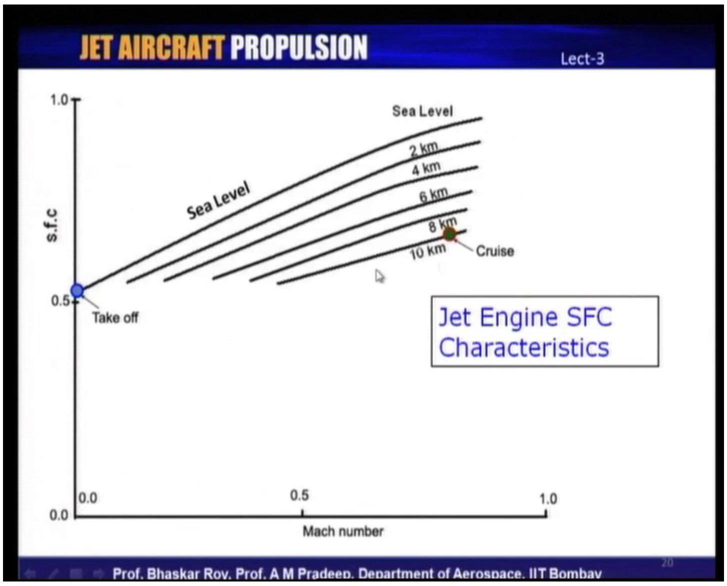
Jet Engine Thrust Characteristics

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Let us take a look at the overall thrust characteristics of a typical jet engine and as we see here the thrust characteristics have been computed typically for at various altitudes starting with sea level, then 2 kilometers and going all the way up to 10 kilometers which is often a good cruise altitude for many of the aircraft that are flying around.

What we see here the y axis is the thrust ratio between the instantaneous thrust and the take off thrust which is as I mentioned earlier quite often in the maximum thrust and this is the thrust with which the aircraft engine takes off and then it fly’s at sea level. At a certain point of time, it starts climbing to higher altitude and finally, reaches the cruise altitude where it cruises to long distance and that is when the mach number is also supposedly the cruise mach number whatever the aircraft is designed for. Now, this is what we see here is that the thrust characteristics at any altitude is more or less flat. At lower altitude, the thrust slightly decreases with the increasing flight mach number and that is due to the ram drag at very high altitudes, the ram drag is less because that high altitude, your here density is much lower. So, with flight mach number, the thrust characteristics actually shows a slight upward trend rather than a downward trend as you see in the lower altitudes. However, at all altitudes, they are nearly constant and this is what we had discussed today earlier on.

(Refer Slide Time: 49:08)


JET AIRCRAFT PROPULSION

Lect-3

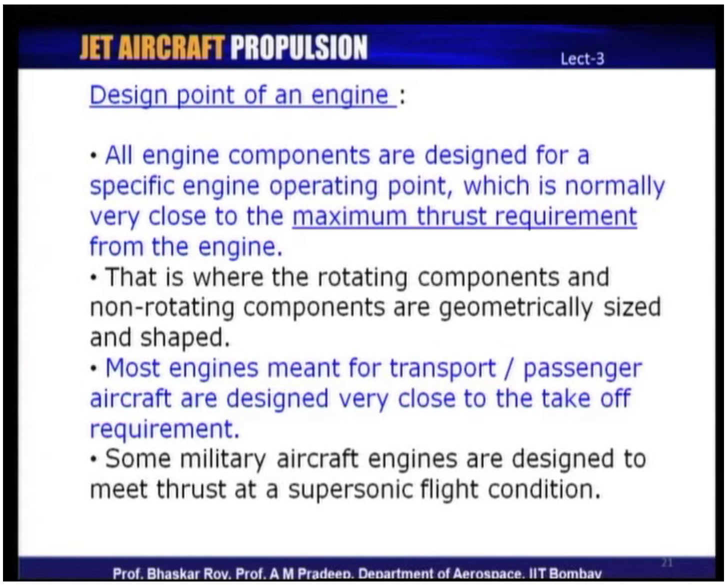
Jet Engine SFC Characteristics

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

If you look at the sfc characteristic, a specific fuel consumption at sea level, they keep on increasing at all altitudes. Indeed they keep on increasing, but at higher altitudes. As we can see the s f c is lower even if they are increasing. What is interesting is that the actual value of s f c as we see at take off and as we see at cruise may be more or less equal. It may be possible to design an engine where the cruise s f c is actually slightly lower than take off or it is possible that the cruise s f c is of the same order or in fact, slightly higher than the take off s f c.

So, these are the s f c characteristics of jet engines, typical jet engine at various altitudes with varying flight mach number.

(Refer Slide Time: 50:08)



JET AIRCRAFT PROPULSION

Lect-3

Design point of an engine :

- All engine components are designed for a specific engine operating point, which is normally very close to the maximum thrust requirement from the engine.
- That is where the rotating components and non-rotating components are geometrically sized and shaped.
- Most engines meant for transport / passenger aircraft are designed very close to the take off requirement.
- Some military aircraft engines are designed to meet thrust at a supersonic flight condition.

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Now, many of these engines as I have been mentioning a design to operate under certain operating conditions, a particular point at which the engine is designed or all components of the engine are designed is referred to as a design point and this design operating point or engine operating point is normally very close to the maximum thrust requirement which is quite often that take off operating point of the aircraft. Now, this is the design point at which the rotating components and the non-rotating components are geometrically sized and shaped. Once they have sized and shaped, that shape is what it exits with.

So, this is what it is designed for most engines meant for transport have passenger are designed very close to the take-off. Many of the military aircraft on the other hand, are designed to meet the thrust at supersonic flight condition. That means, an aircraft engine typically designed for supersonic flight, it is lightly to have it designed point at a supersonic flight condition. So, the designed point of an engine needs to be fixed a priory before the engine is designed which means the engine designer needs to know where this engine is going to be used. Whether it is going to be used for a passenger aircraft or it is going to be used for a military aircraft and of what kind. Only then the engine design can be proceeded with.

(Refer Slide Time: 51:59)

Off-design points of an engine

All the engine operating points other the "design point" are known as the off-design operating points. At all these operating points all components of the engine must work together in a matched manner (as an unit) to produce thrust. The aircraft, on which the engine is mounted, must also work within this thrust envelope. Thus, before an engine is mounted on an aircraft a very elaborate aircraft-engine analysis procedure is normally carried out.

That stands to reason that all other operating conditions of the engine along with the aircraft are known as off-design operating conditions or off-design operating points. At all these operating points, the engine must work together in a matched manner. That means, all components of the engine must work in a matched manner as an unit to produce thrust that is required by the aircraft and it is necessary. Then, that the aircraft on which it is mounted must also conform to this thrust envelop. The thrust characteristic that we just had a look at, we will have a quick look at this. Thrust characteristic is what is created by the engine or the engine designer. It stands to reason that the entire aircraft should also operate within this thrust envelop.

So, the aircraft operating envelop must fall within this thrust envelop of the engine and this thrust envelop includes all the operating points which indeed are the design point. So, this takeoff point is the design point of the engine. All other operating points including the cruise operating point is off-design operating points of the engine.

So, let us try to understand that all engines are designed to operate over a large number of off-designing operating points and we have to make sure they operate efficiently at all these off-design operating points. So, in this class, we have just had a look at various kinds of parameters that define an engine and help us creating an engine to meet the requirements of an aircraft flight.

In the next class, we will look at various variance of turbojet engine with and without reheat. We will also look at jet engines which are single spool and multi-spool. These are the mechanical variations and we will take a look at what this mechanical variations really mean and to what extent these are designed to meet the requirements of various kinds of aircraft.