Introduction to Airbreathing Propulsion
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Lecture – 40
Centrifugal Compressor

Okay, so let us continue the discussion on this turbo machinery what we are looking at is the equation of the torque and we have looked at the general equation of the turbo machinery of the and then what it needs is that now in addition to your mass conservation, momentum conservation and energy conservation, you need one more equation which is the conservation of the angular momentum.

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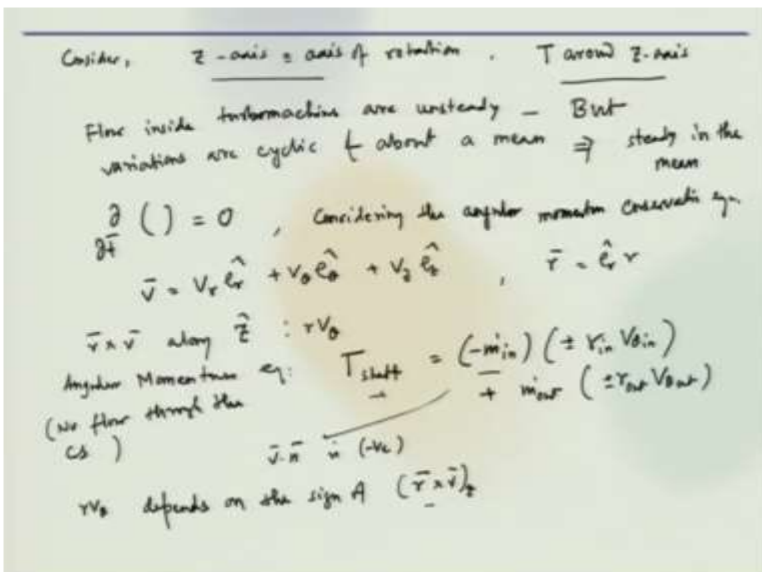

And so we are looking at how to derive that and now we are simplifying for the other turbo machine systems, so this is where we actually got to that when you have the system considering that the rotation is about z axis and you get the torque equation like this.

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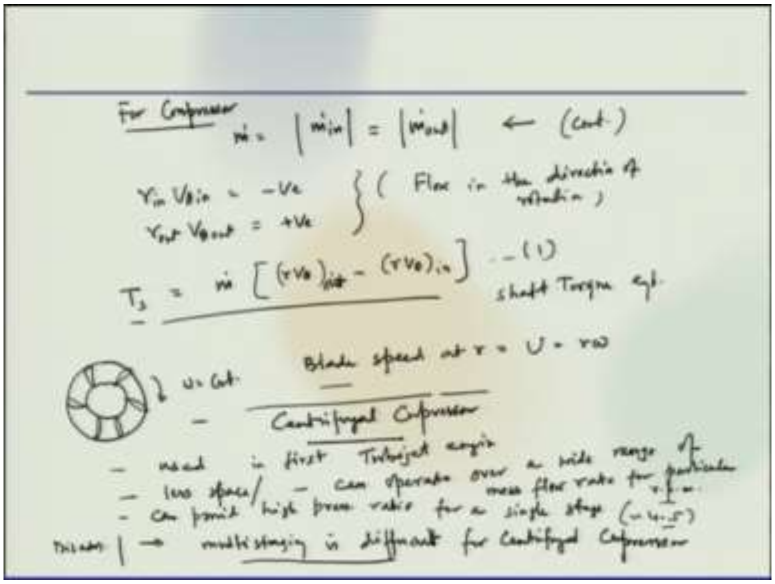

Now, let us say if you for compressor, if you consider compressor because this equation is valid for both turbine and compressor, now let us consider compressor here. So, for compressor what happens your

$$\dot{m}_{in} = \dot{m}_{out} = \dot{m}$$

so this comes from my mass conservation equation or continuity equation. Now what will happen, $r_{in}V_{\theta,in}$ is negative because the flow and $r_{out}V_{\theta,out}$ will be positive.

And that is because my flow in the direction of rotation, okay so my torque equation

$$T_s = \dot{m}[(rV_\theta)_{out} - (rV_\theta)_{in}]$$

so this is known as shaft torque equation, okay and the T_s is the torque applied by the shaft of the rotor. Now, if you let say, if you consider a compressor, take a compressor like this where you have these are the blade of the compressor, so this goes in the rotation like this.

So, the angular velocity omega which is let us assume this is constant, now the blade speed at the radial distance r, so the blade speed at r would be U,

$$U = r\omega$$

so this is how you can find out different velocity triangle. Now, this is how whether it is a compressor or turbine using this sub torque equation, we can actually find out the equation for a compressor or the turbine. Now, let us continue the discussion where we start with the discussion on compressor and even in the compressor.

We will first do discussion on the centrifugal compressor, so the other is a brief history of centrifugal compressor, this is probably the first turbojet engine which when you talked about the history and all these. The first turbo jet engine actually used, so the centrifugal compressor was used in first turbojet engine. Now, the advantage here of the centrifugal compressor which we will look at it in details as we go along.

But just to give you an idea actually, the it occupies less space, so the size is or rather you can think about it that is occupies a smaller length than an equivalent axial flow compressor, so this also can operate over a wide range of mass flow rate for a particular rpm because when you talk about all these turbo machines, the rotation is an important factor and when you talk about the rotation, there is the rotation per minute which is an important thing, so for a fixed rpm, it can operate.

Secondly, it can also can provide high pressure ratio across a single stage or for a single stage. So, typically a centrifugal compressor can give you a pressure ratio of typically roughly 4 to 5 over a single stage, now what is the disadvantage is that to obtain very high pressure ratio in modern gas turbine engines which is an important thing to discuss. So, all these modern engines require high pressure ratio, now to obtain that you require multi staging but with the centrifugal multi staging is not straightforward or rather difficult here for centrifugal compressor.

So, one can say that to obtain a high pressure ratio for this modern jet engines, multistage axial compressor are often used because multi staging is quite difficult for centrifugal compressor. So, I mean as you can see, there are certain advantages, there are certain disadvantages which are associated with centrifugal compressor but one thing is quite natural is that for a single stage, it can provide higher pressure ratio compared to same of an axial compressor.

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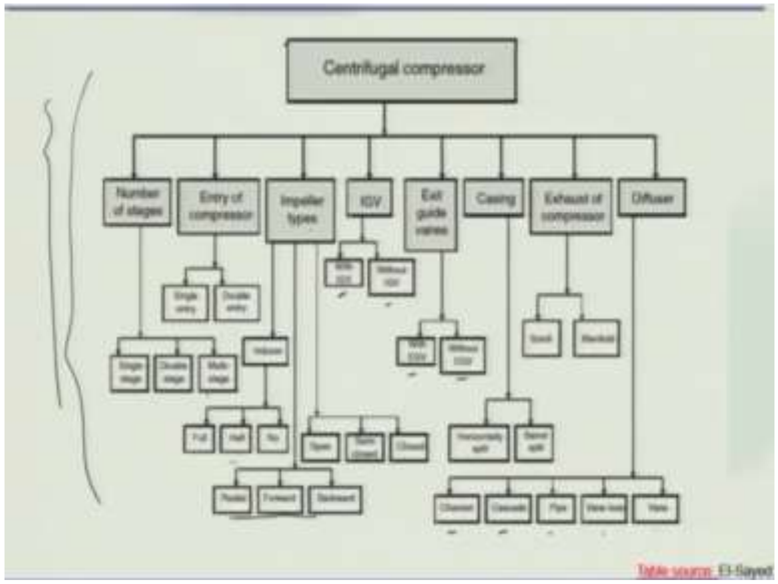

And also now, this if you look at the classification of the different kind of centrifugal compressor, this actually takes into account of lot of the things, I mean it starts with the number of stages, I mean, this one can think about the different kind of components or different type of centrifugal compressor which possibly can be there but then what are the other complications that can have.

So, let us look at that briefly but as I mention, centrifugal compressor was initially or first used in the first turbo jet engine, so that is the one of the nice history which is associated with the centrifugal compressor. Now, number of stages if you look at it, so it could be single stage, it could be multistage, it could be double stage, so there is the possibility but as I said multi staging is not that easy.

Now, entry of the compressor, it could be single entry or it could be double entry, now there are different kind of impeller, so one type could be inducer, then there are other variations here, full, half or no, there could be radial forward or backward type or you could have open semi closed, closed. So, I mean even there are mix and matches like radial open, radial semi closed, radial closed or forward open.

So, all these permutation and combinations are also possible, then you have IGV which is called inlet guide vane, so one possibility it could have a IGV, one possibility could be without IGV, at the same time you could have exit guide vanes, so with EGV, without EGV. Casing; it may have horizontal split, it could have barrel split and then you have exhaust of the compressor could be scroll manifold, then you have different kind of diffuser vanes, it could be channel type, cascade type, pipe, vaneless, vane.

So, all these; if you put together, you can think about the complications of a system which could be there, I mean this actually also include different mix and matches.

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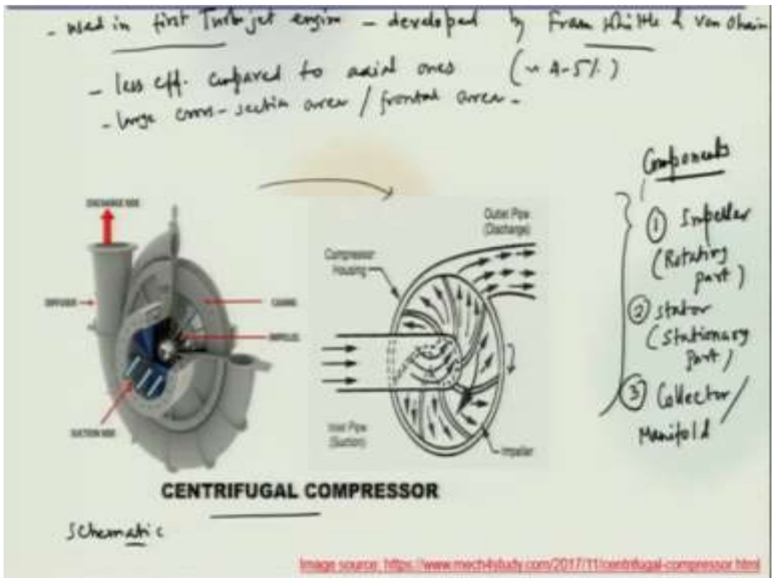

So, this is one of the images of a centrifugal compressor, one can see I mean, it will give you an idea how it looks like, so this is what the inlet side, when it comes in, so this is the another schematic of here, so from here to here you can see this fluid comes in here, goes through this impeller, so these are this what you see here, these are the impeller blades and flows goes through that and finally goes out radially, this is the discharge side.

And the different components, so that is one of the schematic of it and if you look at the component, there is a suction site, these are impellers, then there is a casing, there is a diffuser, these are all different components, I mean as I mentioned this was first used in the earlier days in the first turbo jet engine which was developed by so used in first turbo jet engine which was developed by Frank and Whittle; by Frank Whittle and Von Ohain.

So that is the first turbo jet which was introduced and there the compressor which was used, there is the centrifugal compression, so I mean you can go and look at the different books or the images across Internet and find out different kind of axial schematic or the picture of these, so that will give you an, the idea here is that you can have an idea how is centrifugal compressor look like.

But now, this was firstly using in turbo jet but later on as I said with the development of the modern gas turbine engine or the aircraft engine, so you require different, so more and more axial kind of compressors are preferred or often used and then multi staging is very much there which is in a difficult task when you actually try to use centrifugal compressor, so that is why the use of centrifugal compressor in the modern gas turbine engine has become quite less.

And then other things which could be associated with that is that compressors are; the centrifugal compressors are slightly less efficient compared to axial ones, so that is typically it could be roughly 4 to 5% less efficient, okay and then not only that it also has large cross section area or one can say frontal area, okay. So, once you have this kind of thing, so these are the different things which is sort of gone into the little bit of disadvantages of but till even today, there are certain systems where centrifugal compressor is preferred compared to axial one.

Let us say, for example you need higher pressure rise within a small space or confinement you will go with this kind of setup. Now, moving forward a centrifugal compressor or rather the layout of a centrifugal compressor has 3 major component; one so these are the components of the system, so one is the impeller, so this is the primary rotating part, so that is an important component like here, which is sitting on a shaft and this is what it actually rotates. So, this guy goes in rotation and that is what we have these dynamic system.

Then one can have stator which is the stationary part and third one could be the collector or manifold, so collector or manifold, so which is sort of denoted by the scroll or volute, so this one can say this is called the volute and something, so these are the important component of that centrifugal compressor which should be there.

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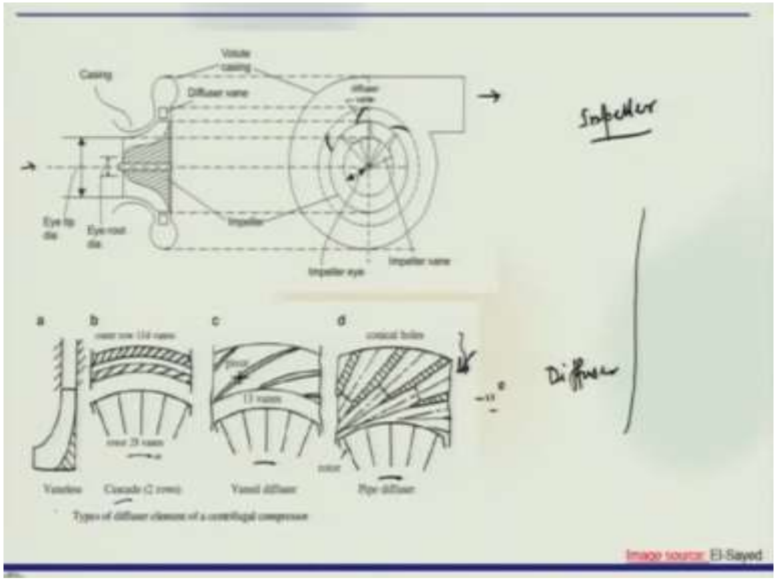

Now, if you look at this portion of the image, this is the portion which you call the I mean, this cut section if you take it, this is how it looks like and this is how the other side, so you can see this is the impeller, this is the shaft, then you have diffuser vane and the side view of that and this is the volute casing, so these are impeller vanes which are here, then tip diameter, root diameter all these different things.

So, the whole idea of this impeller is that when the fluid comes through, it actually goes through the rotation and finally goes out in the radial directions and these are the different components of it, so it will give you an fair amount of idea, what it can be and then the other is the diffuser, so there are also different kind of, so this is the impeller part as I said or the rotating part, so this is the diffuser part typically for centrifugal compressor, this is more like an static component.

So, you can have vaneless diffuser, you could have cascade kind of diffuser, you have vane diffuser of different cadre, you can have conical holes all these different kind of diffusers you can have. Now, if you look at this you have this channel kind of diffusers or channel and pipe diffusers which are more suitable for aero engines and gas turbine because both of these diffusers are actually they are able to collect the flow in separate passages then diverges slowly.

And the pipe consist of conical hole with which has a rectangular section like this, one can see here in this picture particularly and one pair of the opposite valves they are diverging, these divergence angle is roughly 11 degree, so 10 to 11 degree roughly that, so different kind of diffuser that one can have and that brings to a different kind of setting of the central compressor which we have seen it. It could be single stage, multistage or singles entry, all these different kind of classifications which are possibly one can have, okay.

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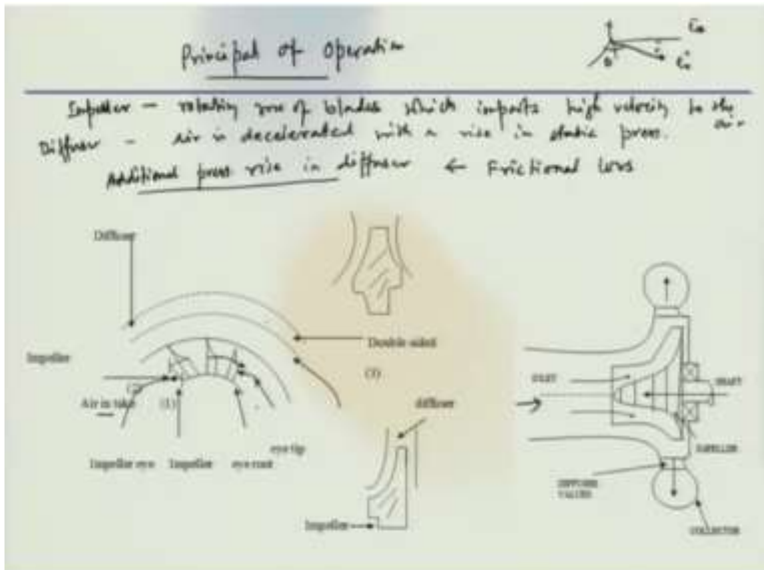

Now, so we can looked at the how it operates actually, so looks at the principal of operation, okay so this is the another schematic here, there are different station number, so you have this thing, the axis which is like this that could be theta, r, this is er, then e theta, so this is impeller I, this is I root that is the I tip and the impeller goes like this, there is a diffuser, so double sided one, so one can look at side way, this is the what flow comes in through this, goes through the impeller, goes out through this.

And as I said impeller has this rotating row blades which imparts the rotating row of blades which imparts high velocity to the air, okay and the diffuser, so it has a number of fixed diverging passages in which air is, so air is decelerated with a rise in static pressure, okay. So, what it happens; actually air is sucked in, so this is what the air intake, air is sucked in into the impeller eye and it goes in the swirling motion or whirled around at high speed by the vanes or the impeller vanes on the impeller disc.

So, this actually introduces the centripetal acceleration to the air with corresponding pressure rise, corresponding rise in static pressure from the i to t, so when the thing goes from the i to the tip of the impeller, now this is the dynamic pressure rise or due to the rotation there would be pressure rise, then when it passed through the diffuser, there is also a component of the static pressure rise.

So, that means in centrifugal compressor you have additional pressure rise in the diffuser or the diverging passage of the diffuser but obviously, one has to take into consideration the frictional losses, frictional loss, there would be some loss in stagnation pressure due to friction. Now, when one does the design in typical scenario, the design practice is the half pressure rise in the impeller, so impeller does the half of the pressure rise, then half of the pressure rise happens in the diffuser part. So, at the exit of the impeller, the blades are straight which we have already seen and in radial direction that is why the flow predominantly remain radial in the other direction, okay.

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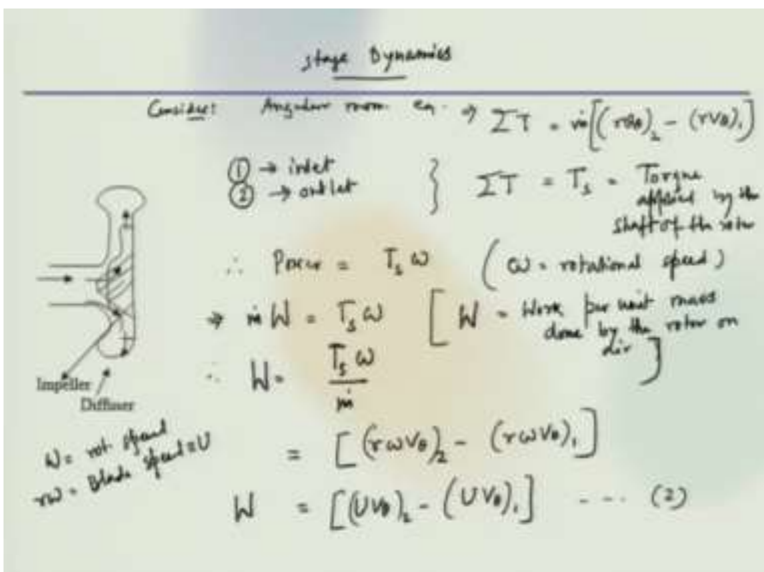

Now, you take the simpler portion and then look at the stage dynamics, so this is centrifugal compressor stage dynamics, now we consider the angular momentum equation which is

$$\sum T = \dot{m}[(rV_\theta)_2 - (rV_\theta)_1]$$

so this is as per this notation where this is 1, this is 2. So, one can think about 1 corresponds to inlet, 2 corresponds to outlet, okay so and summation of T would be the Ts, so this is the torque applied by the shaft of the rotor.

Now, if you estimate the power, then it has to be, power would be

$$power = T_s \omega$$

where ω is the rotational speed, okay. So, now one can equate

$$\dot{m}W = T_s \omega$$

where this W is the work per unit mass done by the rotor on air. So, once you equate this you will get

$$W = \frac{T_s \omega}{\dot{m}}$$

which one can write that

$$= [(r\omega V_\theta)_2 - (r\omega V_\theta)_1]$$

okay so this is what we get. Now, ω is the rotational speed, so this is the rotational speed and $r\omega$ would be the blade speed which is U, then I can write this

$$W = [(UV_\theta)_2 - (UV_\theta)_1]$$

so this is our equation 2, okay.

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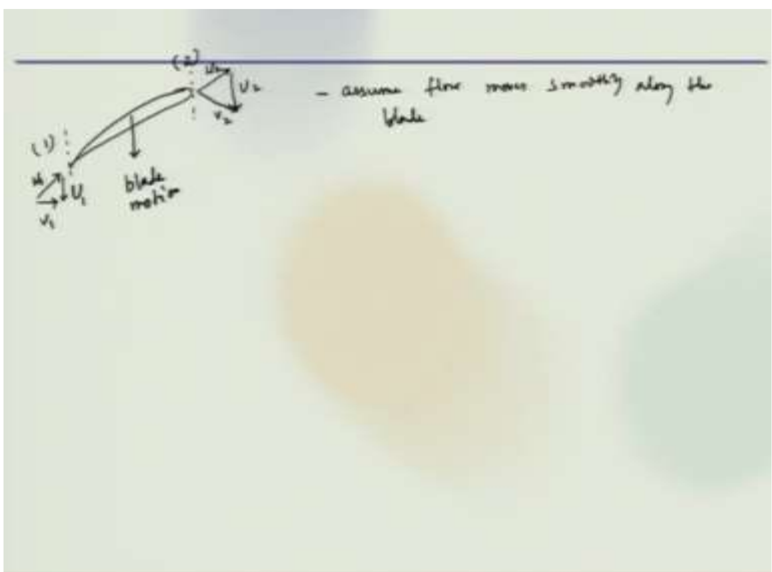

Now, if we let say assume or rather consider a blade, let say we consider a blade, compressor blade which is in motion, so this is my blade motion, now this is leading edge, this is trailing edge, so this would be my one station 1, this could be my stations 2, so this is how the velocity triangle would look like here, this is v_1, this could be W_1, this could be U_1 and the same time here, this could be W_2, this could be U_2, this could be v_2.

So, if you assume that assume flow move smoothly along the blade, so there is no other distortion or anything, so then you can have this, so how it looks like then when the blade is in motion, so we will stop it here and continue the discussion in the next lecture.