Introduction to Airbreathing Propulsion
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Lecture – 39
Introduction to Turbomachinery: Basic Principles and Equations

Okay, let us continue the discussion and now we will continue the discussion on turbo machinery, so far we have talked about all the cycle analysis part and now, we will move to the rotating part. So, now this is one of the important components of this gas turbine engine.

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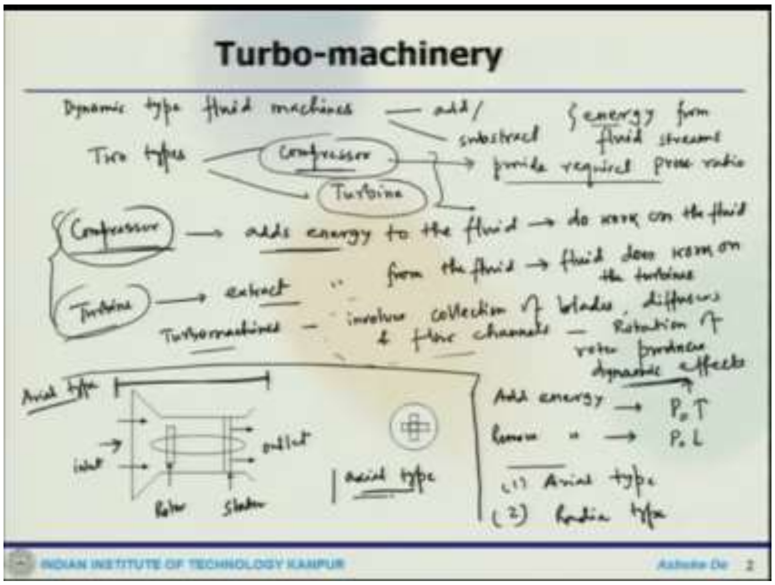

So, let us look at what we are going to talk about in turbo machinery, so essentially what we need that when you talk about this turbo machinery, these are dynamic type of fluid machines, so these are dynamic type fluid machines. So, what is the purpose of this, why we talk about; we will come back to this figure later one and the purpose of this dynamic type fluid machine is that we can add, either we can add or we can subtract energy.

So, using the flow around those components, we can add or subtract energy from fluid stream, so the whole idea is that while the fluid passes through this kind of machines or the components on the unit through the mechanism, we actually extract the energy which allows these things to provide power to the rest of the components and since there are rotating components, we call it the rotating machinery or turbo machinery.

So, there are primarily, there are 2 types of systems or the dynamic system or the turbo machinery, one is obviously the compressor which we have been talking about that because this is one of the very, very critical component which is required for this gas turbine operation because this is the component, where actually you get pressure rise and then the other component which is the turbine.

So, I mean as you recall from our earlier discussion which we have been talking about these 2 components in the gas turbine engine, they are; see the compressor; the purpose of the compressor is that provide you the required, provide the required pressure rise, okay. So, this allows the fluid when it passed through the compressor from the intake to before entering to the combustion chamber, it passed through the compressor.

And compressor units actually compresses the air and then it allow you to or provides you the required pressure rise, so that pressure rise is very, very important later on of these different components to extract more energy and end of the day, the whole idea is that you can generate the required amount of thrust and the second component is the turbine, now the turbine actually where you extract the energy out of the fluid stream.

So, there is I mean, 2 basic differences; one is compressor, and other is the turbine, what compressor does that it is actually, if you look at the working principle, I mean nevertheless whatever we talk about here this is give you the global idea about how compressor and turbine works but we will go into the details and that is what we specifically named this section as the turbo machinery section.

Because we are going to talk about all these different components, their operational principle, their design, how things actually happen there, what are the issues, so this guy actually adds energy to the fluid, at the same time if I look at the turbine, there is a basic difference. What turbine does; turbine actually extract out, so that extract energy from the fluid. So, immediately you can see one adds energy; one extracts energy.

That means, in time one can say the compressor actually it does work on the fluid that is what it does and the other hand, the turbine it is the reverse, where fluid does work on the turbines, so there is a huge difference between these 2 operation of these 2 components; one is compressor, one is the turbine. So, one can see when it adds energy that means, if you look at from the basic energy conservation principle, the compressor adds energy to the fluid stream.

That means, it requires some external energy to be given input, so compressor actually absorbs energy and at the same time, turbine extract energy out of the fluid stream, so now when you talk about this turbo machines, this all this turbo machines in a group of these compressor, turbines and all these that involves collection of blades. So, all these turbo machinery they have a collection of blades, they have diffuser and flow channel.

So, these are there, now when it actually rotates this whole combination of this flow channel blades, diffuser around and proper casing, they go in the rotation and the rotation of rotor actually produces the dynamic effects, so these dynamic effects what we say here either these could add energy to the fluid or it can extract out the energy from the fluid. So, if it adds energy to the system, then this is the actual behaviour or working principle of compressor.

On the other hand, if it extracts out the energy out of the system, so this is what we call turbine or the system is called turbine, so which means, so all these turbo machineries or the turbo machines, these are collections of blades, diffuser, flow channels and the rotor components, all these different components which are involved there and the due to the rotation of this rotor that produces this thing.

Now, another simple thing is that when you talk about adding up the energy or when we add energy it actually the stagnation pressure increases, when you add energy to the fluid it increases the stagnation pressure, while when you remove energy it actually decreases the stagnation pressure. So, now this is what you can absorb as the basic components and the basic working principle of this turbo machines.

And there are 2 different types, I mean in the primarily, there are; so one can call it a aerial type, second one is the radial type, so the schematic picture here which is actually a picture of an aerial type dynamic system, so this is the rotor, this component you can think about stator, so this is another view of that. So, the rotor is rotating, stator is there stagnant, so while rotor rotates these dynamic effect comes into the picture and this is where the fluids comes in and goes out.

So, whole idea is that; so most of the things which will comes in and comes out, if this is your inlet and this is your outlet, then from inlet to outlet, the flow component pretty much remains in the axial directions or in one direction, so this is one call it aerial type or this one can also say these are the axial type, so which means the flow comes in pass through the rotor, stator or the collection of rotor and stator and then finally goes out.

So, across this component you get your desired work to be done whether adding of energy or extraction of energy, so essential work done takes place here and the fluid passed through these components, so this is called the axial type machine.

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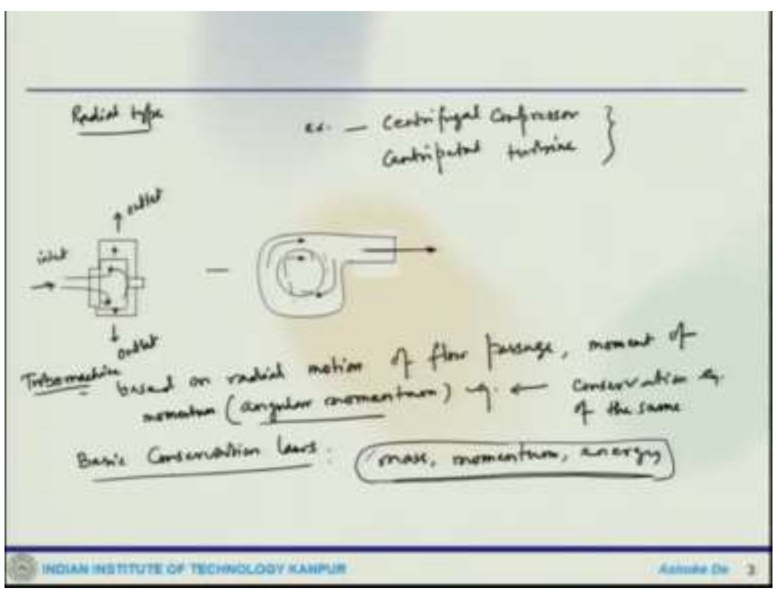

Now, the second one, this is another picture what one can think about it is a radial type dynamical system or radial type turbo machines, so what it does that, flow may so this could be the inlet, if you can see the flow comes in this way, goes through this internal component here and then finally goes out like this, so these are my outlet. So, flow comes in axially but goes out radially that is what these are called the radial type of system.

And this is another view of that when flow comes in, then there is all this rotating takes place inside that and finally goes out radially, I mean flow comes axially, goes out radially, so that is what it called the; now, one can take some example of radial type system; one is the centrifugal compressor, this is one which is actually known as a radial type compressor or radial type turbo machine or one can think about centripetal turbine.

So, this is another radial type system, there are other radial type dynamical system also, now for this kind of radial type system, the machine is or the turbo machines is based on radial motion of flow passage, okay, so what happens is that angular momentum or moment of momentum which is called angular momentum. So, you have angular momentum equation and that is going to be an important parameter or rather the conservation equation of the same.

So, when we talk about this turbo machines, all these turbo machines or the dynamical machines, I mean what we have looked at so far, when you actually try to analyse one of the system, we talked about primarily the system which are actually I mean, required some of this conservation law or basic conservation laws which includes the mass conservation, momentum conservation, energy conservation.

So, these are all important conservation laws which we have so far dealt with except the one which are going to now talk about is the conservation of angular momentum, since we are dealing with this rotating system, now this becomes quite important that we should also look at the conservation of angular momentum. Now, going back to our previous discussion; mass momentum or energy we have been dealing with for different system and the different parts of this gas turbine engine. So, we are only going to look at the conservation of angular momentum then while we move forward, we go more into the details of the same.

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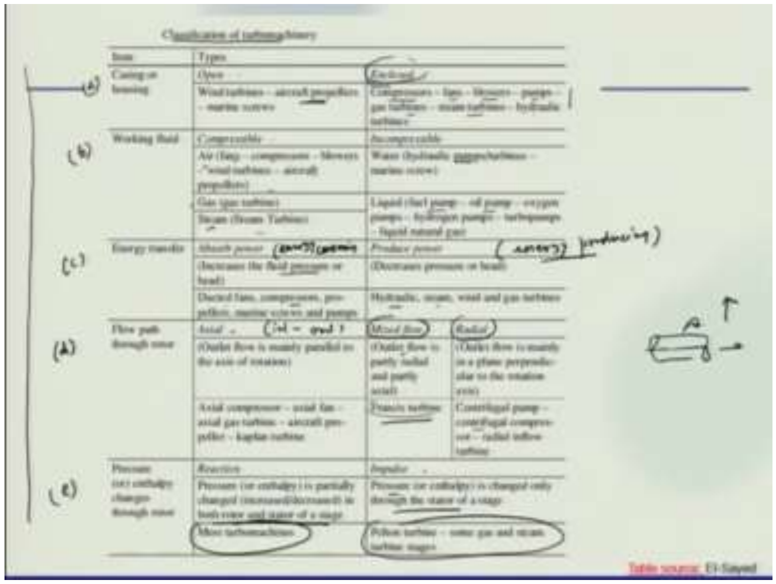

Now, just to have that classification of the turbo machinery, this particular table gives you an broad idea or rather detailed idea about the classification of these different kind of turbo machine systems or dynamical systems. If you start with the top, the top you see that you have its; so these items are depending on which the classification has been made, so one which you start with the let us say casing or based on housing.

So, if the casing is either it could be open or it could be enclosed, if it is open then it is a wind turbine or you can think about aircraft propeller or marine screws, so these I hope you have seen all of these, so these are open type and the blades are rotating, whether it is the aircraft propeller or screw or wind turbine, the blades are rotating and you have seen this because there is no casing, so it is exposed to the open atmosphere or air, that is why these are called open casing based this thing.

Now, when you go to that the same time, this enclosed, then it could be compressor, it could be fan, it could be blower, pump, gas turbine, steam turbine, hydraulic turbine, so all these different kind of turbo machines they come under the enclosed category. Now, while dealing with this gas turbine engine or aircraft engine, we are dealing with fan, we are dealing with compressor, we are dealing with turbines, so these are the components or of our discussion so these are all enclosed type.

Now, depending on the casing; second is that when you look at the working fluid, so it could be again categorised in 2 different component; one is the compressible, one is the incompressible. So, let us look at if the flow is compressible, so if the flow is compressible than air is the working fluid, so which is used in fan which can be used in compressor, blower, turbine, aircraft, propeller or it could be; now, if you talk about gas turbine engine, then you use gas, steam turbine engine is the steam.

So, these are the working fluid or other case in incompressible range, you could have water, where hydraulic pumps are hydraulic turbine or marines screw, you could have liquid which uses fuel pump, oil pump, oxygen pump, hydrogen pump, turbo pumps all these uses different kind of liquid fuel so, depending on the working fluid you have a category of that. Now, the third one how you actually transfer the energy?

So, is there whether you are observing power or you producing power, so that means it is actually energy consuming device, so I would say energy consuming and this case energy producing, so depending on the energy transfer you can have 2 more categories, so one could be ducted fan, compressor, propeller, marine screws, and what happens here, it increases the fluid pressure and the head.

So, we have already seen that when you talk about the compressor actually, compressor does the pressure rise, so when the fluid passed through the or air pass through the compressor, you get pressure rise, this is where; as a system or component compressor actually consume energy but it does the work on the fluid. On the other case, it is the energy producing device obviously, it could be hydraulic, steam, wind, or gas turbine.

So, fluid actually does the work on the blades of the turbine or this turbo machines, so you are able to produce the energy, so based on the energy transfer you could have 2 different component. Now, fourth you can have the flow path through the rotor, which we just talked about, it could have axial that means from inlet to outlet, everything goes axially, so inlet to outlet, so these are called axial or the outlet flow is mainly parallel to the axis of rotation.

So, that means if you have this kind of shaft sitting there and then the axis of rotation, the flow goes out, so this is what you call it axial, axial compressor, axial fan, axial turbine all these are axial flow machines or it could be the other extreme could be radial, when the outlet flow is mainly perpendicular to the rotation, so if this is rotating like this, flow goes out in this direction, so that makes it the radial centrifugal pumps, centrifugal compressor, radial flow turbine.

Or you can have in between the mix flow, that means outflow is partially radial and partially axial, so that is one kind of turbine which is known as Francis turbine, so this anyway we are not going to talk about this respect to the gas turbine engine, we will be looking at the centrifugal compressor, axial compressor and the turbine all these. Now, lastly you can have pressure change or enthalpy change through the rotor.

So, you could have reaction machines or you could have impulsive machines, what happens in the reaction machine; pressure or enthalpy is partially changed, it could be increased or decreased in both rotor and stator of the stage, so this is most of the turbo machines are reaction, kind of reaction based or other case, in impulsive case, pressure or enthalpy is changed only through the stator of the stage.

So, the Pelton turbine, some gas or steam turbine of these kind they actually fall under this category but whatever we will do the discussion, they will be mostly of the reaction type, so one can see if you look at this table that one can distinguish this turbo machines in a different brand of categories depending on what you talk.

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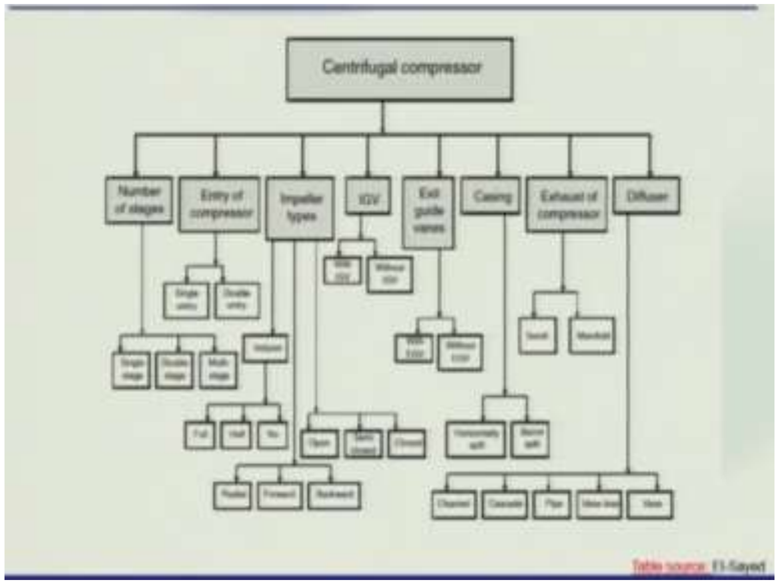

Now, particularly we will be talking about centrifugal compressor here and I mean, we will start with the; so let us see how the governing equations of the turbo machinery, then we will again come back to that.

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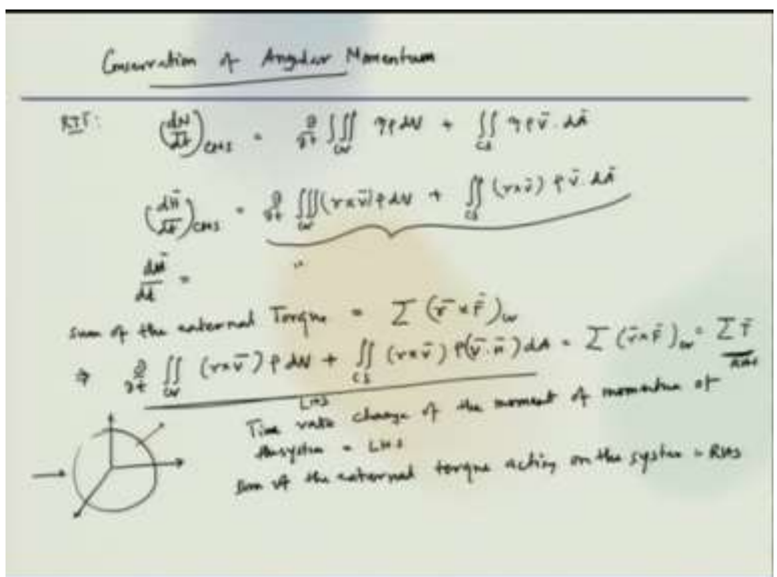

So, we said that we need to have the conservation of angular momentum, so that is what we need to have, so we will start with the basic Reynolds transport theorem during which we have discussed earlier, what it talk about

$$\left(\frac{dN}{dt}\right)_{CMS} = \frac{\partial}{\partial t}\iiint_{CV} \eta\rho dV + \iint_{CS} \eta\rho\bar{V}\cdot d\bar{A}$$

Now, N is the property so we will put here in the angular momentum, so this is for control mass system, this is

$$\left(\frac{d\bar{H}}{dt}\right)_{CMS} = \frac{\partial}{\partial t}\iiint_{CV}(r \times \bar{V})\rho dV + \iint_{CS}(r \times \bar{V})\rho \bar{V} \cdot d\bar{A}$$

So, which turns out that I can write, dH by dt equals to this right hand side what we have, so this whole thing we will come here, now sum of the external torque, so

$$sum\ of\ external\ torque = \sum (r \times F)_{CV}$$

then we can write down this equation as

$$\frac{\partial}{\partial t}\iiint_{CV}(r \times \bar{V})\rho dV + \iint_{CS}(r \times \bar{V})\rho \bar{V} \cdot d\bar{A} = \sum (r \times F)_{CV} = \sum T$$

okay.

So, it just one can write this and if you see the; write down the; so this could be the axis and this is how the things comes in, goes out, which says that time; so this is the time rate change of the angular momentum or momentum of the system, so this is time rate change of the moment of momentum of the system equals to the sum of the external torque, which is here acting on the system.

So, this time rate is this is what we say, let us say left hand side, this is my left hand side and some of the external torque acting on the system is right hand side, so this is what RHS, so that is what we can like this.

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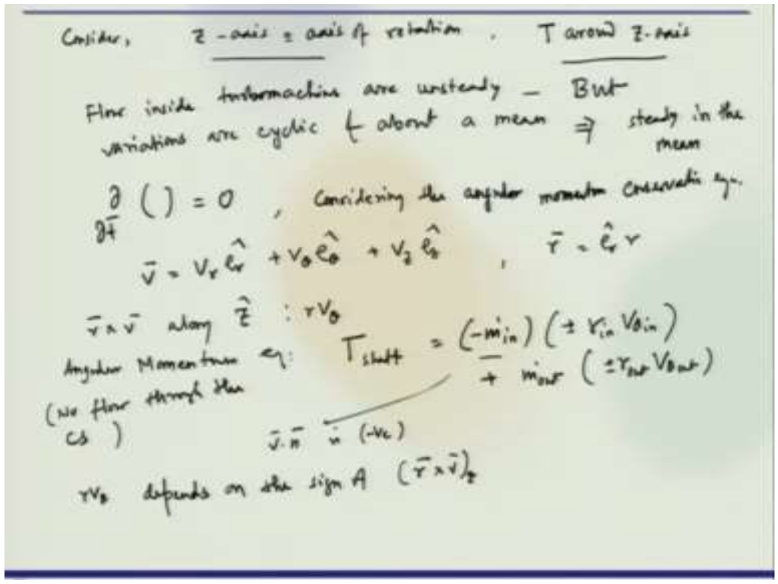

Now, if we consider a rotating axis let us say, consider a rotating device as let us say, z axis equal to the or rather equivalent to the axis of rotation, so we are considering that for a particular machine, z axis becomes the axis of rotation. So, what we are interested is that we are trying to find out the torque around this z axis or z axis, whatever you call it, so the axis of rotation is around z axis, then we want to find the torque around this z axis.

Typically, the flow in the turbo machinery is unsteady but so one can think about the flow inside turbo machines are unsteady, okay but the variations or cycle or the variations are rather cyclic and about a mean but variations are cyclic in nature, cyclic and about a mean, so this kind of flow is called the steady in mean, so which means the flow is steady in the mean. Let for a flow which is steady in mean, the term del del t of these becomes 0.

Now, when you consider in the angular momentum conservation equation, so considering the angular momentum conservation equation and across the control surface, you write

$$\bar{V} = V_r \hat{e}_r + V_\theta \hat{e}_\theta + V_z \hat{e}_z$$

and what you have,

$$\bar{r} = r\hat{e}_r$$

now what you can have $\bar{r} \times \bar{V}$ is along z which is rV_θ. Now, I can write the angular momentum equation, I can write that as

$$T_{shaft} = (-\dot{m}_{in})\left(\pm r_{in} V_{\theta,in}\right) + \dot{m}_{out}\left(\pm r_{out} V_{\theta,out}\right)$$

so this in and out represents the inlet and outlet, okay.

So, you also assume there is no flow through the control surface, so the minus sign in $\dot{m}_{in}$ because here $\bar{V} \cdot \bar{n}$ is negative, now there are plus, minus signs also sitting here, $\pm r_{in}$ and $\pm r_{out}$, so which means the rV_{θ} depends on the sign of $(\bar{r} \times \bar{V})_z$ which is essentially determined by the using the right hand rule. So, we will stop here and continue in the next lecture.