Non-conventional Energy Resources
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Lecture - 39
Flywheels

(Refer Slide Time: 00:15)

Hello, in this class we will talk about a particular form of energy storage device, which is referred to as the flywheel. We have spoken about other energy storage devices particularly we are very familiar with batteries, because we use them in a number of applications including you know remotes, toys or mobile phones. So, a variety of places we end up using batteries. So, we are and we replace the batteries.

So, as the battery gets exhausted we tend to replace the battery we recharge the battery. So, there are so many activities that we do that bring us or make us very aware that there is a battery in the in the you know device that we are using. So, this is how we are you know quite comfortable and quite conscious of the fact that there are batteries in many of the things that we use.

Interestingly flywheels are also there in several of the you know devices that we use or at least that we have used. And it is just that we don't there is no formal recharging of the flywheel and there is no formal replacement of the flywheel we don't do those kinds of

things. So, many times we don't even know that there is a flywheel inside, we just use it we don't realize that there is a flywheel and we take it for granted. In fact, I guarantee you that I mean I am pretty sure I am pretty sure. In fact, other and that is the reason I say I guarantee you that for sure you have used something that had a flywheel in it, and as we look through the examples you will understand why that is the case. I am going to show you some really commonplace examples where we use them and also the more you know sophisticated possibilities that we are looking at.

So, that's the thing that that's the thought that I would like you to have in the back of your mind, that it doesn't matter you know what your background is or where you are from, this almost it is almost guaranteed that you have used a flywheel of some sort. So, that is the point that I wanted to highlight here ok.

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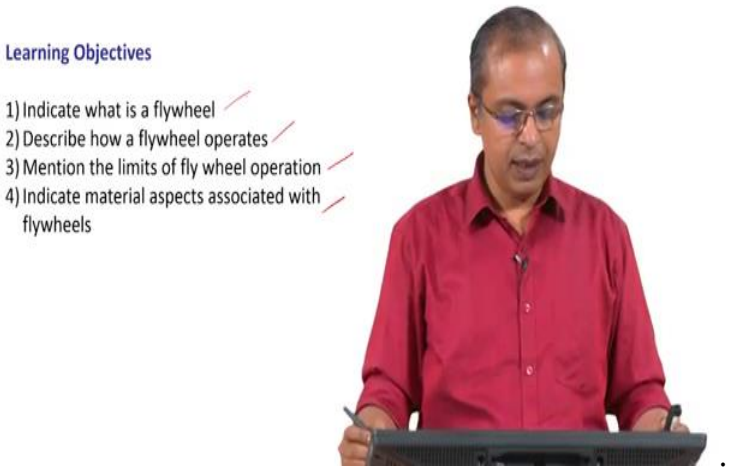

So, in this class our learning objectives are of course, to indicate what is a flywheel. So, first let's get some clarity on what is a flywheel and because I am I am going to keep telling you that you are using it anyway and we will see will describe how it operates, what is the basic idea behind it's operation, we will try to understand what are some limits of the flywheel operation. So, that we get some sense of what's possible in it, and you know up to with what kind of range we have to stay in this. So, and then finally, we will finish up with some material aspects associated with flywheels, We look at you

know what is the kind of material that is used, what are the possibilities and what are some you know pros and cons of those materials.

So, this is the basic set of learning objectives we have. What is a flywheel, how it operates, what are some limits in it for it and what are the materials associated with it that is our learning objectives.

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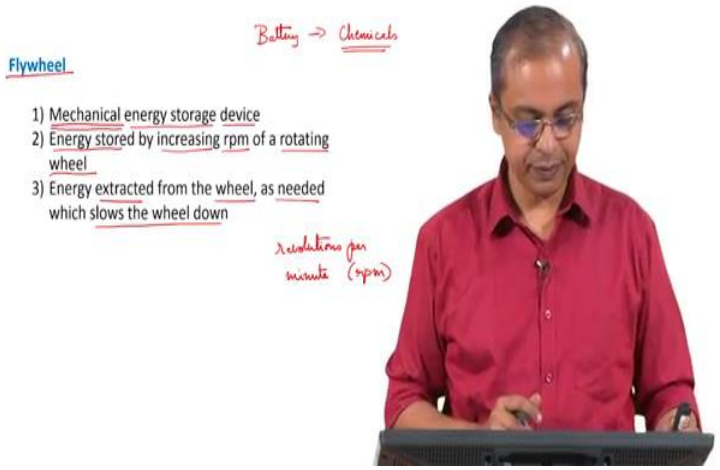

So, what is a flywheel? So, a flywheel is basically an energy storage device ok. So, it's an energy storage device except that it is a mechanical energy storage device ok. So, when you look at a battery, that stores energy using chemicals. So, that's battery is also an energy storage device, but there the energy is stored using chemicals. So, there is some chemical reaction in one direction and if it's a rechargeable battery there is a chemical reaction the opposite direction so, but there is chemicals there are chemicals there that that store the energy and we understand that you know there is a delta h associated with the reaction and from that you can get some information about the you know kind of energy that is there in the reaction, and then from there you can get the you know delta g and as well as the open circuit voltage for that reaction, standard electrochemical potential for the electrodes all of that we can do.

But that's got to do with the fact that there are chemicals there and we have electrochemical reactions. Whereas, in a flywheels there are no chemicals in the sense that there is no reaction that is happening there, there is no chemical reaction that is

happening there, there is only something mechanical that is happening there. So, there is energy in something that we are already doing, and this mechanical event picks up that energy and holds it, and then when we want to we want that energy back it releases it back to us ok. So, therefore, it's a sort of a mechanical event or a mechanism that pulls up the energy and then stores the energy and therefore, it's a mechanical energy storage device ok. And the basic idea is that energy is stored by increasing the rpm. So, that is revolutions per minute.

That is what I am referring to as rpm which of course, you are familiar with it. So, energy is stored by increasing the rpm of a rotating wheel. So, there is a wheel that is rotating, you increase the rpm of that wheel and then in the process it stores up energy and then you can extract that energy back from the wheel. As needed and of course, as you can imagine when you extract the energy back from the wheel it will slow down it will slow down the way.

Of course, in the extreme case the wheel comes to a complete halt. So, the in which case you have extracted all the energy that the wheel had, so you have extracted the energy out of the wheel and it comes to a complete halt. So, basically you are already doing something, where you have a lot of energy in the form of say kinetic energy or whatever it is, and then that energy gets transformed transferred to a mechanical device which consists of a rotating wheel ok.

So, so that wheel could have been stationary also to begin with; it could have been stationary and then you have this energy, then it picks up that energy and therefore, starts rotating. So, that's also possible or it could already be rotating and you simply increase the rpm of that rotating wheel and therefore, that energy gets stored because of the angular you know velocity of that wheel which is being, which is either going from zero to something higher or is already at some value and goes to an even higher value and then as you extract it out it is handing it back to whatever system that you want and then it therefore, gradually slows down. So, this is the basic idea and so, that's the way in which the Flywheel operates.

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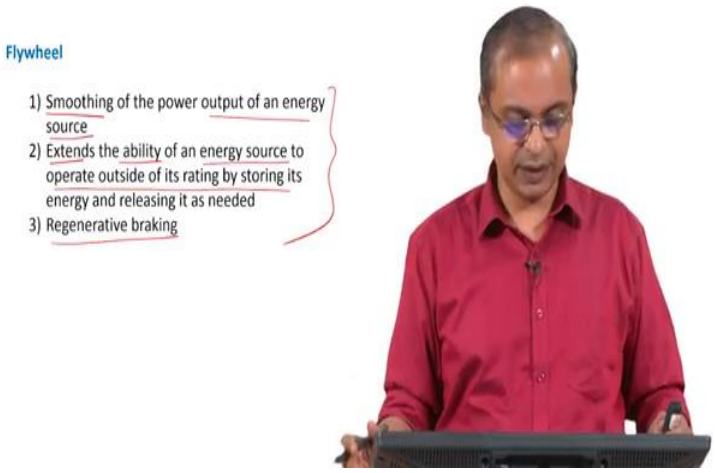

So, for example, what is the Flywheel used for.

So, some of the things it gets used for is smoothen smoothing the smoothing of the power output of an energy source. So, many energy sources don't have like a continuous you know delivery function so to speak. So, if you look at energy as a function of time, it may be it may actually have a cyclic you know a manner in which it delivers the energy. So, there may be if I were doing something where for part of the cycle it delivers energy for part of the cycle it is not really delivering energy, again part of the cycle it delivers energy.

So, this kind of a thing might be going on based on what is happening in that energy source, how it is generating the energy, how is it conveying that energy out into the external system right. So, whereas, many times when we are using the energy, when we are utilizing the energy we want smooth availability of the energy. So, we have lights. Lights fall on us and so, in our house we are using house you know lighting system.

So, but this lighting system we want know steady light it is very distracting if the light keeps flickering on and off in fact, it is it is worse than not having the light right. So, at least not if you don't have the light your eyes are if you keep on having this flashing light which is going on and off that is extreme you are knowing distracting possibly even very bad for the eyes.

So, if your energy sources an on off on off profile and you simply connect lights to it, then this is what we are going to have we would not have lights that go on off on off on

off. So, on the other hand if you have something like a flywheel in the system, and you if you if you figure out a way in which you can implement the flywheel in the system then the flywheel will take this energy which is on off on off on off and make it some smooth average value ok. So, that's the nice thing about it, it makes it a smooth average value.

So, maybe your light will not be as bright as you can have it when it is fully on, it will be a little less bright, but it will stay steadily on. And as I said for most of us that's a much better situation much more desirable situation, we do not really want a flickering light. So, we want a steady kind of light and so, that's the kind of thing that as flywheel does.

And that's just an example I am just telling you about an light that is flickering on and off, but many other activities also you have an engine that is running, you don't want the engine to go on off on off on off it is a very jerky kind of movement you are sitting in a vehicle you keep on getting jerked back and forth, because the engine is switching on and switching off repeatedly. So, the flywheel then ensures that you get maybe less power than the peak power of that engine that's putting out, but it will stay steady. You will have it steadily available to you, then the vehicles run smoothly, you don't you know get pushed around back and forth and it runs smoothly.

It also helps us extend the ability of an energy source to operate outside of it is rating ok. So, in other words something may not be able to give as much power, but because you have a flywheel, you can actually store up much more energy in the flywheel than is being given by the you know energy source at a given point in time and then deliver it faster than the energy source.

So, the original energy source may not be able to give this much energy in such a short period of time, but it can give you energy steadily. So, the flywheel stores up that energy steadily and then it releases it to you at a faster rate then the energy source can do. So, so in some sense it extends the operating window of some energy storage device, and we will see for example, how it is used for something like regenerative braking. So, that is something that we look.

So, there we are doing the opposite where you already have energy out there and you are trying to you know remove that energy from the system, the regenerative braking is a way in which you take up that energy and store it in some you know some fashion

without just wasting it as heat. So, this is the thing. So, these are some interesting ways in which the flywheel gets utilized in various energy applications.

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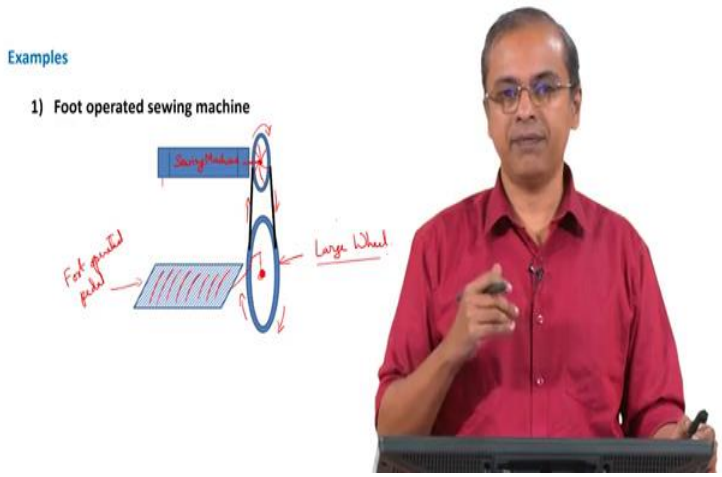

So, now even though flywheel is something that you know sounds like a very strange concept, I told you that it is something that all we are almost guaranteed that we have all used at some point in time. In fact, this is not even the example that I will tell is the most common example, but we will get through some examples and then you will have some sense of what I mean by saying that is a very commonplace thing.

So, if you look at the you know manual sewing machines. Of course, these days if you go to many shops, they are not using manual sewing machines, they have a motor because electricity is available and they want to remove the drudgery of you know regular work where people keep on doing this with their like moving their foot back and forth, because that is a repetitive movement and can actually over a period of time do damage to their peoples feet right. So, therefore, that it is not desired, but at the same time if you look at the old designs of sewing machines, this is what they had they had one will giant wheel at the bottom and then you had a foot operated pedal.

There is a foot operated pedal here. So, that is what you have out here, and there's a large wheel right. So, you keep you operate the pedal a few times and this wheel picks up speed ok. So, it starts rotating fast after a while you can take your foot off the pedal ok. So, when this wheel rotates. So, let's say it is rotating like this, then because of this belt

that is here the belt goes up and belt comes down it makes the smaller wheel also rotate like that ok.

So, tha's the basic action that we have, and then there is some you know some axle here some shaft here, which is connected to this wheel that is out here and that rotates. So, that rotates this whatever are the machinery inside this machine. So, this is the sewing machine. So, it operates something inside it and then you have some needle out here, which gets your job done. So, some needle out there which goes back and forth and get some job done.

So, that's the way in which the sewing machine operates right. So, now, the point is that you keep pressing this pedal a few times and then this you know there is some mechanism which connects the pedal to the wheel and that gets the wheel to rotate. So, some mechanism which gets the wheel to rotate and then that that wheel keeps rotating and then the machine runs. The point being that when you take your foot off the pedal, the wheel continues to rotate and that is because it has picked up angular momentum there is inertia, there is inertia in that wheel and that inertia as you know by definition implies that if an object is stationary, it will continue to remain stationary if it is if object is moving, it will continue to remain moving until it is acted upon by some external force right.

So, either stationary or moving object will continue to be in a state of rest or in state of motion, until it's acted upon by some external force that's the basic idea of inertia we are just using it in the form of you know inertia of a rotating wheel.

So, we have a real wheel which has some mass associated with it, it has the moment of inertia associated with it, which is the equivalent of mass in a in the in a rotating object and then as you rotate it, it continues to rotate. So, even if you stop take your foot off, you are no longer providing energy for it, it continues to rotate, it rotates the small wheel on top and you continue to be able to operate the sewing machine. So, this idea that you have this wheel that continues to rotate even after you have stopped providing it with energy, that is the idea that the basically the idea of or an implementation of this flywheel. So, that's the basic idea right. So, this is an example that many of you I am sure have seen, but like I said it is not just about what you have seen, it is also about

what you have used. So, there is there are some versions of these flywheels, which you have for sure used and we are going to see that.

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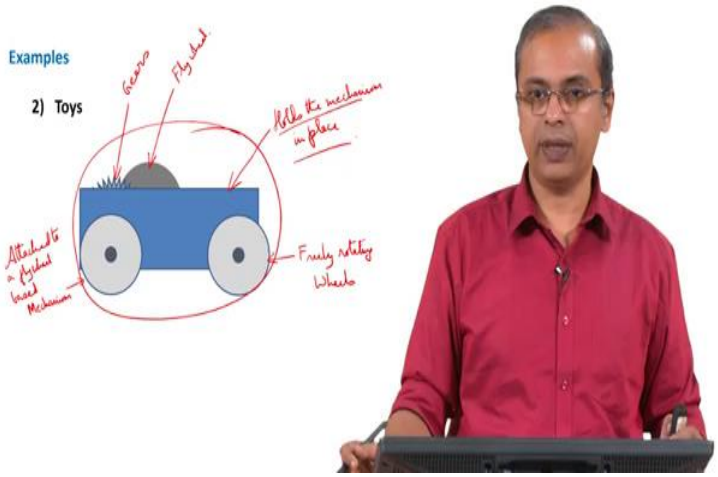

And that comes from your toy ok. So, almost all of us have used toys where you basically have no battery in the toy, you can have various versions of it, you have one where you just basically push it and then it just has because you pushed it, it continues to run freely there is no motor in it, there is no mechanism in it, the it just rolls it rolls till friction stops it right.

So, that is one version of it. There is another version of the toy, where you actually have to push it I mean you know push it against the ground a few times and the wheel picks up some speed, then you release it on the ground it will continue to run ok. So, then there is something inside which seems to have picked up the energy. So, initially you have to push it hard on the ground you have to push it a few times hard, then you will find even if you take it off the wheels are rotating and it is a you can feel that even if you put your hand to stop the wheel there is a resistance.

The wheel continues to push your hand and continue to work so; that means, it has got something more than the free wheels that are rotating in the front right. There will be two wheels in the front which are freely rotating. So, let me say these are freely rotating wheels. So, you have some toys, some car or whatever it is and the toy car the front two

wheels may be freely rotating. So, you. So, when you push the car on the ground and then you pick it up, the front wheel also rotated the back wheel also rotated.

But once you take it off the ground will find that the front wheel more or less immediately comes to a halt, but the back wheel continues to rotate okay that is because the back wheel is attached to a mechanism. So, the back way the rear wheel rear wheel of this vehicle is attached to a mechanism that is based on a flywheel ok. So, it is based on a flywheel. So, that flywheel is what you see here, you see that flywheel sitting up here and it is based on that mechanism.

So, that flywheel is picks up that energy and then continues to release that energy gradually. And that is why when you lift this vehicle off the ground it does not stop the rear two wheels do not stop the can they continue to run and they run for quite some period of time, based it really depends on how much energy how effectively you pushed energy into the vehicle, how quickly you move the vehicle a few times and then you take it off the ground you can see. And then even a you know several seconds later you put it on the ground it will continue to run, it will run for quite some distance before it halts.

So, this is a toy most of us or the with this implementation of the toy you may have bought you know different kinds of toys whether it is a car or a bus or whatever it is, you may have physical shape of the rest of the toy is just you know cosmetic. It's all just something that makes us feel happy when you buy the toy. Internally the mechanism is exactly the same across several toys.

So, you will have us if you open up the toy you will find a mechanism that looks something like this inside that, you will have some box which seems to contain the mechanism and holding this mechanism in place is very critical because the wheels are linked up to the mechanism in a particular manner and that is why this box is critical although it just seems like a small box inside, that box holds many of these things correctly in position. so that this energy can get transferred to this flywheel. So, this by the way is the flywheel and these are some gears ok.

So, this is a this is a flywheel and those are some gears that you can see, and I am going to show that to you in little greater detail, but that's how the energy gets transferred to the flywheel and then re released from the flywheel. So, I just make it a little bit more transparent. So, you can see what we are dealing with here, you just see an opaque box

here which is holding the mechanism, I will start making it a little transparent. So, you can see how the mechanisms.

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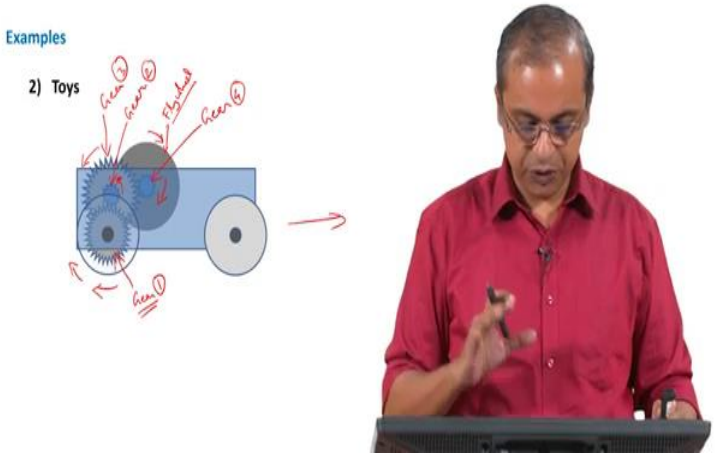

So, you can see inside these two wheels are there I showed you that this is a gear, that was the only gear that was visible at that point, now you see more gears here you see one more gear here and you see some more gears here right. So, a lot of such gears you begin to see, and then if I make it more transparent you see one more gear here right.

So, all of them are they are there here also you have one okay so. So, now, I will just remove all the wheels and we just have the gears up there. So, that you can see what is happening so, but basically the point being when you push this vehicle on the ground. So, this means this wheel rotates this way, because this is the forward direction, you are trying to push this vehicle forward and then the wheel rotates backwards.

So, when it rotates this gear this gear, let me say this is gear 1 gear 1 also rotates in the same direction, that forces gear 2 which is out here gear 2 to rotate in this direction ok. So, gear 1 is rotating clockwise, it is forcing gear 2 to rotate anti clockwise that is forcing gear 3 which is attached to gear 2 also to rotate anti clockwise, that forces gear 4 to rotate clockwise and that that gear 4 is attached to the flywheel. So, the flywheel also rotates clockwise ok. So, the flywheel is here.

So, that is the flywheel. So, the flywheel is also forced to rotate clockwise, but you will notice here that this gear 1 is larger than gear 2. So, therefore, it forces the gear 2 to rotate very quickly relative to you know whatever rpm is therefore, gear 1 gear 2 will have a much higher rpm, the gear 3 is attached directly to gear 2 therefore, gear 3 will have the same rpm as gear 2, and then gear 3 is attached to a smaller gear out here which is gear 4 and so, the gear 4 will actually operate at higher rpm than gear 3 and that higher rpm is now available to the flywheel. So, that is how the you know as you rotate the as you move the toy, progressively you are increasing the rpm and therefore, the flywheel is actually rotating at very high rpm. So, I will I will remove all the rest of it so that you just see the gears here.

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So, that's what that's the exact thing that you see here like I said this rotates this way that rotates the other way, that rotates that way and when that happens this rotates this way, the flywheel rotates this way. And you can see progressively it is getting faster and faster and faster. So, the flywheel rotates very fast ok.

So, the flywheel rotates fast. So, that is the way in which this flywheel is operating and so, if you if you just go back here this is the toy.

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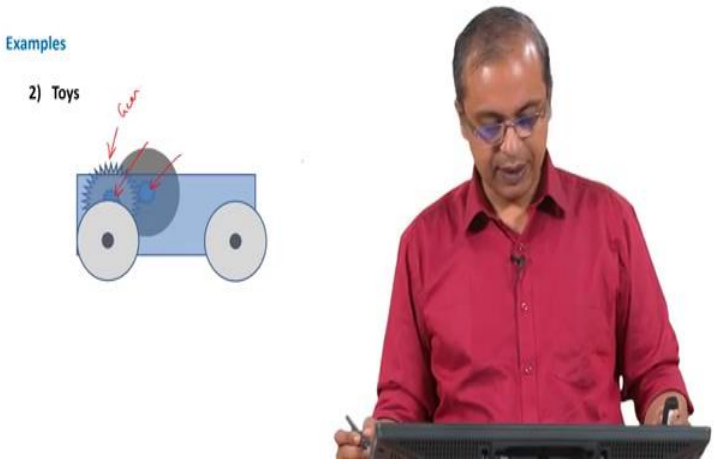

You can see the gears that are there and you can see all of the gears now and you can see how they are operating and then you have I separate all the other components out and you only see the gears right. So, this is what we have. So, in this process the flywheel gains a lot of energy and it has that energy in it is rotating very fast, and the gear ratio is such that it will it will be able to deliver that power back to those wheels, once you know pull this vehicle back down. It will run slower, the wheels will run slower than the flywheel, because that's the ratio in which the gears are there, but there will be a lot of torque that will come available from the flywheel, because of this advantageous gear ratio and therefore, the vehicle will run.

So, that's how these toys run and that is why I said I guarantee you that you have used a flywheel, and most likely you have used a flywheel and this is the flywheel that you have used. You can see you know even if you have some children in the in the house and they have a toy that is broken, you open it you will see a mechanism that looks exactly like this. So, this is the flywheel. So, we have all used of flywheel.

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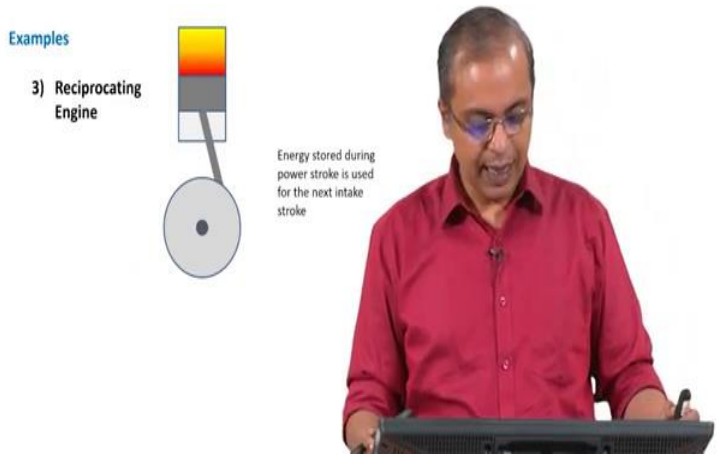

Another example. So, that that's a simple example. So, these were two household examples.

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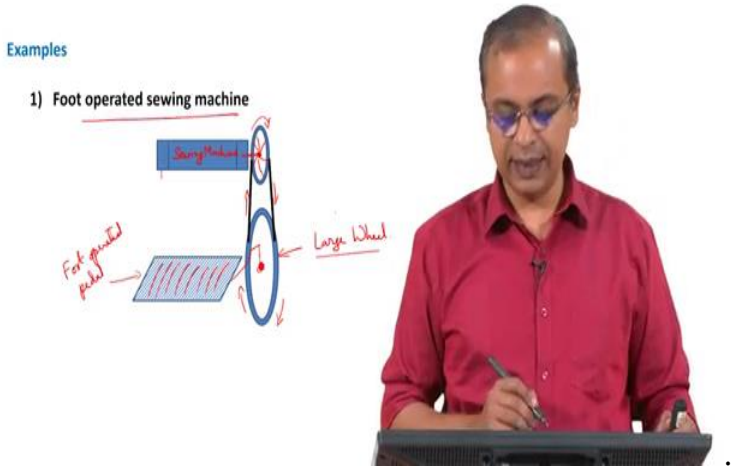

That we that I showed you, many houses do have sewing machines or you can certainly see it in shops at different places, toys we all have seen or used. We also have the same kind of thing in a reciprocating engine. So, in a reciprocating engine you have you know a cylinder in which you have this you know fuel air mixture that comes and then there is it explodes it is lit up and it expands. So, when that happens it moves this piston down okay and so, there is an energy stored there is a power stroke this is the power stroke, this is the this is where the power is delivered from the engine energy is being pushed out

of the engine. So, that makes this wheel rotate ok, because it is linked here. So, that forces this wheel to rotate.

Now, the piston has to go back up. So, that it will get ready for the next stroke right. So, now, there is no reason for it to go back, the only reason it goes back is because this wheel is rotating. So, for example, this is how it will look, as it completes the rotation this is how it will look. So, the reciprocating engine as it completes the rotation during the after the the energy that has been stored during the power stroke is used for the next intake stroke. So, this next in intake stroke that you see here happens only because of the power that it got that this wheel picked up during the power stroke. So, during the power stroke it is rotating, and it pushes back to the wheel it pushes back this piston, and that is how the because this is rotating and then it will continue to do that. It will come back to this side, the next power stroke will push it down and that will continue.

So, even in a reciprocating engine, which is based on some you know internal combustion that is happening, this kind of a mechanism ensures smooth delivery of power. I was telling you, you know that we need to have the power delivered smoothly because here also you see the power stroke is where the power is coming, the intake stroke this now no power that is coming right. So, but this ensures that since the wheel is rotating it is generating this movement that looks relatively smooth on the outside. So, that is the reciprocating engine.

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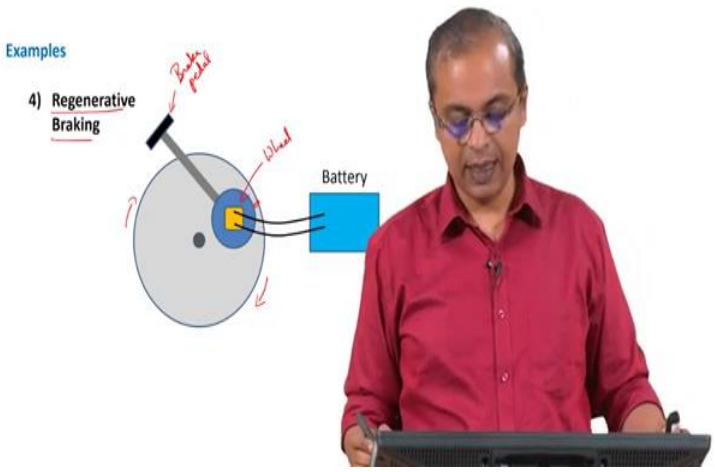

Another example is regenerative braking.

So, in a regenerative braking situation normally in a break in a in a vehicles brake you press the brake of the vehicle, all that you have is that you have the brake pads which press against the you know some rotating disc that is there and then there is friction. So, you have the disc that is rotating and then you have this brake pad that it clips on to that disc because you have pressed the brake, and it grabs it tightly and in the process you have a lot of heat that is generated. You have a lot of heat that is generated and that is essentially that heat is the entire kinetic energy of that car that you had, that kinetic energy of the car is lost as heat in the when you do the braking.

Now, you can think of other implementation. So, I am just showing you one implementation, where instead of just wasting it all as heat you have a situation where let's say this is the brake pad, this is the brake pedal and you are inside the car you have this brake pedal at your disposal and you press the brake pedal right. So, now, this wheel is rotating. So, the vehicle is moving forward the wheel is rotating and it continues to rotate. So, you have another wheel here which is not in contact with that wheel, which is not in contact with your rotating wheel. So, right now there's a gap here. So, right there's a gap that you can see here.

So, there's a gap there. So, that thing it is not in contact, but the moment you press the brake right the moment you press the brake. So, you are here you press the brake. So, when you press the brake, the wheel comes the two wheels come in contact.

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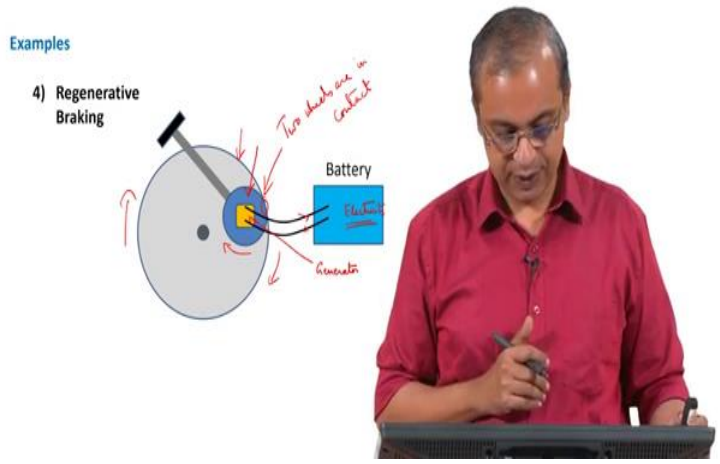

Two wheels are in contact, the two wheels are now in contact when you press the brake. You are here you press the brake you get the two wheels in contact. Once you get the two wheels in contact when you have this rotating this way, you have the this other wheel also rotating the same way right. So, you have the wheel rotating that way, then you can have a generator here and from that generator we have electricity going to a battery ok.

So, that is how we generate electricity put it into a battery ok. So, and this when these two wheels come in contact there is going to be strong resistance from this wheel that is pressing against this smaller wheel, when it presses against this larger wheel it is going to resist the movement of the larger wheel. So, it is going to press against a larger wheel and resist the moment of the larger wheel and so, when that happens, you are breaking you know you are providing the braking energy. So, you are providing the braking energy and it slows down the working of this wheel and therefore, the vehicles slow stall.

So, whereas, previously all that energy was just being wasted as heat, and being you know unnecessarily released to the end where I mean atmosphere, this time when you press the brake you are actually charging you are running a generator creating electricity and charging a battery. So, this idea is called regenerative braking. And I will also point out that regenerative braking you know because it is you know set up in this manner, it is often not ideally suited for sudden braking ok. So, sudden braking where you want you know abruptly you want the vehicle to halt, this may not provide you enough resistance

to the movement of the vehicle to the movement of the wheel, to completely you know stop the wheel abruptly.

So, usually regenerative braking is an additional braking in over and above the normal you know standard kind of break that we have, where we have a pad holding on to a brake pad which presses onto a disc. So,. So, that's always there. So, you always have a regular brake which is available in the vehicle, and you have also this regenerative braking if you decide to implement it. And particularly you will implement it if you have an electric vehicle because you will already have all the electrical infrastructure associated with the vehicle which includes a battery and so on. And so, when you press the brake, automatically some energy goes from the vehicle instead of all of it going into heat, it will go into the battery and a particularly in slow city kind of driving where you are gradually accelerating, gradually deccelerating lot of things are going on, this is an very useful way in which you can recover a lot of energy.

And of course, at the moment you hit the brake hard the there will be some control system which will ensure that your regular brake also comes immediately and then stops the vehicle. So, this is the way you would do it. And this is an implementation I am showing you where we are using our generator to generate the current and put it into a battery. If you are trying to use flywheels in this case we can think of a more or less similar implementation except that it would it would pick up the it would give this energy into a flywheel, as opposed to this implementation where this energy is now being given into a battery. So, you can instead of giving it to a battery you can actually give it into a flywheel and so, that is another possible implementation of this system.

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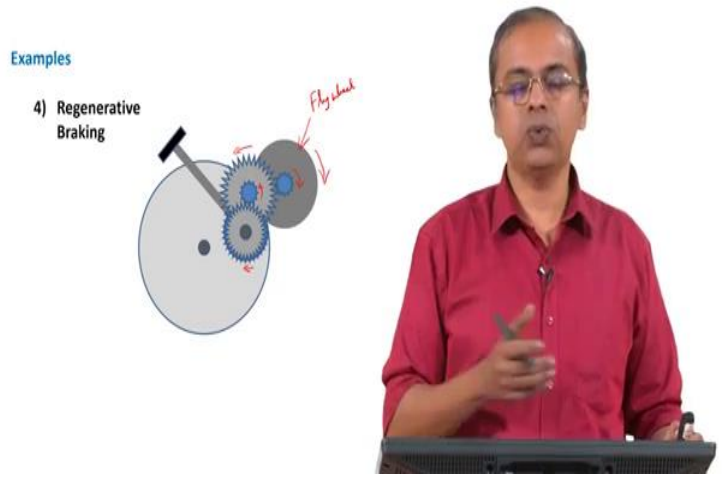

So, for example you would have a situation, which looks where if the brake is pressed like this, in addition to this you know this wheel which is touching the rotating wheel which is the one on the ground, you can have a mechanism attached to it where you have this flywheel.

The same thing that we just saw in the toy. So, you press it and so, it is already there attached to it, I am just showing you as a separate thing for you to understand the how they are related to each other. So, you press the brake down and then when the brake is pressed down, the flywheel mechanism that is attached to this wheel. So, it is already attached to this wheel, which is just not shown in this figure which and it would be attached in this manner. So, that will ensure that this gear rotates that will ensure that that gear rotates, that gear rotates and thus let's show this rotates the flywheel rotates ok. So, in this manner you again convey energy back from the from the rotating wheel which was on the ground, which has the kinetic energy of the vehicle into the energy that is stored in a flywheel.

So, that is the manner in which we share this gather back this energy right. So, this is how you do regenerative braking using a flywheel and electric vehicles do a implement this.

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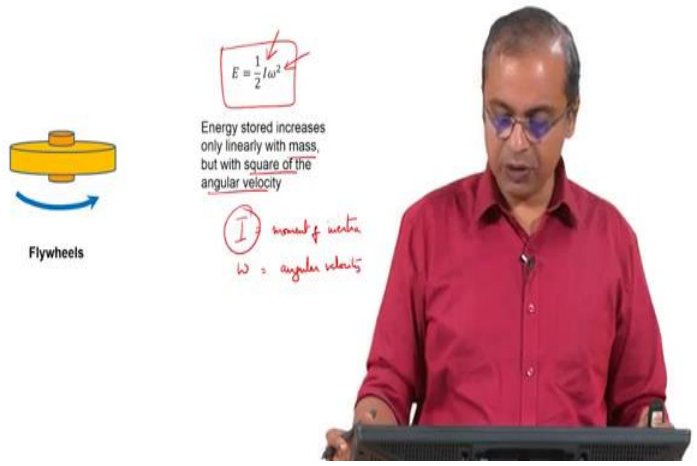

So, now what is this flywheel? So, I we will now look at this wheel alone, this wheel that is out here which is the flywheel, that alone we will look at a little greater detail to understand what exactly is it doing. So, usually what it is that, it is a wheel where there is where you are storing energy in the rotating you know as the wheel rotates. So, if you look at the energy stored in a wheel, it is given by this formula E equals half I omega square ok. So, E equals half I omega square where I is the moment of inertia okay.

It is a I is the moment of inertia and of this wheel. So, and omega is the angular velocity. So, omega is the angular velocity and I is the moment of inertia, and the. So, so when you rotate it this is how the energy is stored in it. So, you can see here the energy increases only linearly with mass, the mass will show up in this moment of inertia. So, it will show up in I the mass shows up there it only. So, you can see I is here in a linear format, but omega is here in quadratic right. So, it's goes. So, as the square of the angular velocity. So, therefore, if you double the mass of the of this wheel you are only doubling the and use the same rpm etcetera you are only doubling the amount of energy that is stored in the wheel.

On the other hand if you double the angular velocity of the wheel, you are everything else being the same you are you know putting four times as much energy into the wheel. So, you are able to store much more energy into the wheel by simply increasing the rpm of the wheel. So, therefore, many implementations of the flywheels focus on this idea that they should try to maximize the amount of omega that or the angular velocity of the wheel. So, that is the implementation that they aim for. That has some restrictions

associated with it that there has some you know limitations associated with it so that we will see in just a moment.

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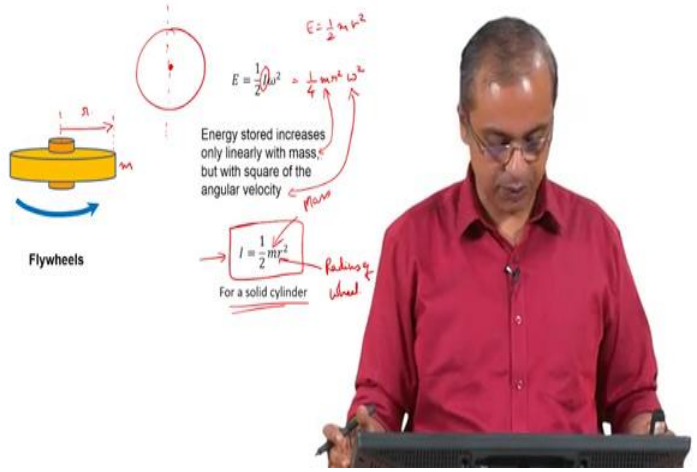

But so, for example, if you look at the I the I is has the moment of inertia for a solid cylinder has this form it is half m r square where m is the mass of the wheel the r is the radius of the wheel.

So, that is this radius here this is the radius. So, that's your radius r and this wheel has a mass m ok. So, you must also remember that you know if you look at you know some information you had in your say mechanics course or so on, the moment of inertia of these kinds of objects or of any object it really depends on the geometry of the object depends on how the mass has been distributed on the object etcetera. So, so for example, this is for a solid cylinder this formula is not going to be the same if you actually have just a wheel where all the masses on the rim. So, you have to actually if you are implementing a flywheel you should figure out what is the shape of the flywheel, what is the manner in which the mass is distributed on the flywheel, what is the orientation in which it is being held in what is the you know axis about which it is being rotated.

So, a bunch of things you have to take into account, before deciding what is this moment of inertia. So, this formula is not standard, it is not standard for all the you know objects. So, whereas, for linear you know for a linear kinetic energy we write E equals half mv

square right we write that for kinetic energy for of something that is moving in a linear which is having some linear motion.

So, there the m is fixed, it doesn't matter in which direction the you are moving this equipment, it doesn't matter if you take a wheel and you throw it this way or you throw it upwards or whatever the mass of the wheel remains the same as long as you are not looking at the rotational aspect of the wheel. The same wheel if I just throw it as a flat object with or without worrying about it is rotation.

If I just throw it, then it doesn't matter in which direction I throw it the mass of the wheel is still m and it's kinetic energy will be given by half mv square. On the other hand if I am not really throwing the wheel, but I am rotating the wheel, then it depends on how I rotate the wheel I could rotate it you know about it's axis. So, I can have a wheel I can rotate it about this axis I can also rotate it about this axis right I can rotate it about a vertical axis, which is the axis that I have put as a dotted line here or I can rotate it about a horizontal axis which is perpendicular to the wheel that that we have drawn here right. So, those two have completely different moment of inertia. So, you cannot use the same i for those two cases you have to you have to check and you have to calculate what the i is, and in that that is the I that you would use.

But in any case the point being that this is the moment of inertia and the m is there. So, therefore, if you just want to write this again as in the with m also included in it, this is E is basically equal to 1 by 4 m r square omega square ok. So, I will remove this here. So, this is E is equal to. So, half mv square m half m r square I have put for this value of I here. So, therefore, I get 1 by 4 m r square omega square. So, you can see here it stays linear with respect to m. So, that is what we say it you know increases linearly with mass, but square of the angular velocity that is the point that you have to note. And that is why they are as working very hard to find ways to keep the angular velocity as high as possible.

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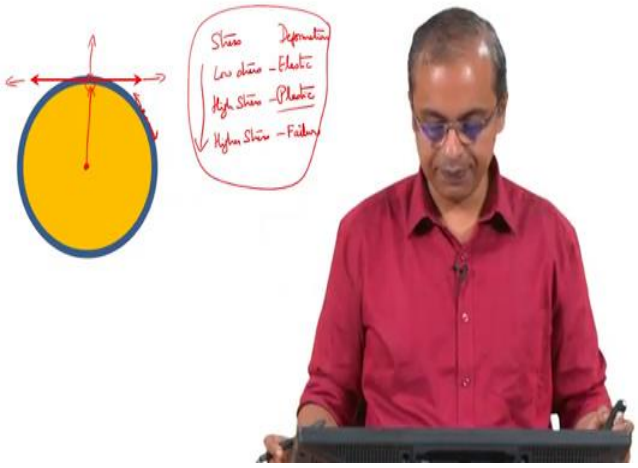

So, what is the problem when you raise the angular velocity to a very high value right? So, when you raise the angular velocity to a very high value. So, if this is the wheel if this is the wheel and this is the center of the wheel. So, you are going to have some centrifugal force ok. So, so this is centrifugal force. So, centrifugal force is going to be that that; that means, what? That means, the material that is at the rim is trying to go away right it is trying to go away from the center and therefore, it is pulling pulling all the material in between to move away from the center and therefore, there is a stress.

Now any material will you can check it's you know tensile strength, ultimate tensile strength etcetera there is when you put stress on a material, it will it will have elastic deformation initially, then it will have some plastic deformation and then it will fail ok. So, it will have elastic deformation, then it will have plastic deformation and then finally, the material will fail.

So, therefore, and that is got to do with stress. So, when you have stress, low stress elastic deformation, high stress plastic deformation and then even higher stress failure. Failure means the material just breaks okay it just splits up into pieces. So, this is just I mean descriptively I have shown in indicated this, actual values will vary and if it is a brittle material for example, you will me you may not see a much of plastic deformation, it will go elastic and you badly see any plastic deformation it will fail. So, so that variation is there for material to material. So, generally, but this is generally the manner in which the material is going to behave once it is stressed.

So, you have centrifugal force, you also have a stress which the force leads to a stress based on you know you put I mean you calculate the force per unit area that is the stress, you also have stress because the circumference is now trying to move apart right. The circumference is all having centrifugal force heading outwards which basically means all these. So, if I take any two points here, if I take a point here and a point here this point is trying to move this way that point is trying to move that way because it is trying to expand and that is basically what I am showing you here, that is the that is the arrow that I am showing you here.

So, it is pushing the material apart that is called hoop stress. So, that's the stress of the rim, which is trying to push the rim open trying to expand the rim. So, you have a circle because the circle is rotating very fast it is trying to expand, the whole circle is trying to expand. So, that is also a stress that is there and that is usually trying to take all the particles that are in that wheel and you know separate them out separate them out to further distances.

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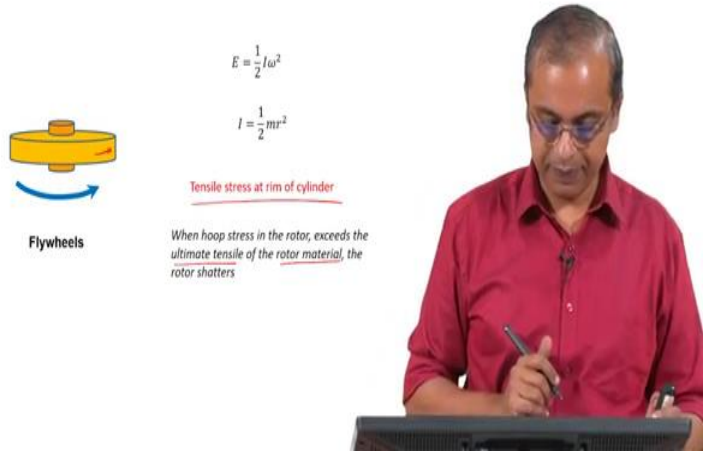

So, usually this tensile stress at the rim of the cylinder of this flywheel at this rim know at the rim of the cylinder is the highest stress that is there in that system as it is rotating at high speeds, and it can make a it creates a situation where the it can exceed the ultimate tensile strength of that material of that rotor material and then the rotor material will simply shatter.

So, that is a safety issue ok. So, the rotor material can shatter. So, in other words if you take a flywheel and you put it at very high rpm, it can basically disintegrate as it is operated ok. And in that sense in in in a fundamental sense, it is the same kind of safety issue that you have with any energy storage device because that much energy is in there. In all energy storage devices it is very critical that you store the energy in a safe manner and extract the energy in a safe manner okay in a controlled manner. The energy should get stored in a controlled manner, the energy should be released in and controlled in a controlled manner. You can create situations or you can end up in situations where either during the energy storage process or during the energy retrieval process the process is not in a controlled manner it can go in an uncontrolled manner.

When it goes in an uncontrolled manner basically you are having a you know an accident so, to speak with respect to that device. So so, that is what we are talking about when we say you know a battery has exploded a battery explode explosion is basically a situation where the energy from the battery got released in an uncontrolled manner, not in the manner that we you want the battery to release the energy, but in an uncontrolled manner; same thing in a flywheel, if you take a flywheel and you get it to operate at conditions which are beyond it's capability, the flywheel will completely come apart; it will just disintegrate into pieces and come apart and that is actually very dangerous. So in fact, you know all the vehicles were they you know install flywheels for various applications. So, certainly like I said you know for let's say electric cars where they are trying to put flywheels to do regenerative braking.

You have to have a casing around the flywheel, which is in a position to handle a breakdown of the flywheel. So, if the flywheel at high rpm just shatters and comes apas comes apart in pieces those pieces should stay within that casing they should not just you know come out and injure somebody or hurt something or caused other damage. So, so it is very critical that when a flywheel is made that it is made in such a way that it is well guarded with, against this possibility that it might shatter and therefore, it keeps the energy in a you know contained manner. And also I will point out that with respect to the flywheels, the bearing is very important. You have to have very good bearings because you don't want friction you want it to run very smoothly and you want it very well aligned you do not want it wobbling when it is speaking of this high rpm, because all those things can be danger. So, dangerous.

So, making the flywheel making good bearings friction as frictionless as possible you never going to have zero friction, but you are going to have as smooth you know well lubricated bearings as possible, which hold the flywheel in you know proper alignment those are all very critical things you know in successfully implementing a flywheel for some application. So, that is something that we have to really carefully look at, because we want it to store a lot of energy and we want it to store this energy in a safe manner. We don't want it to store it in a manner where it will just shatter as it is being operated ok. So, this is the point that you have to keep in mind.

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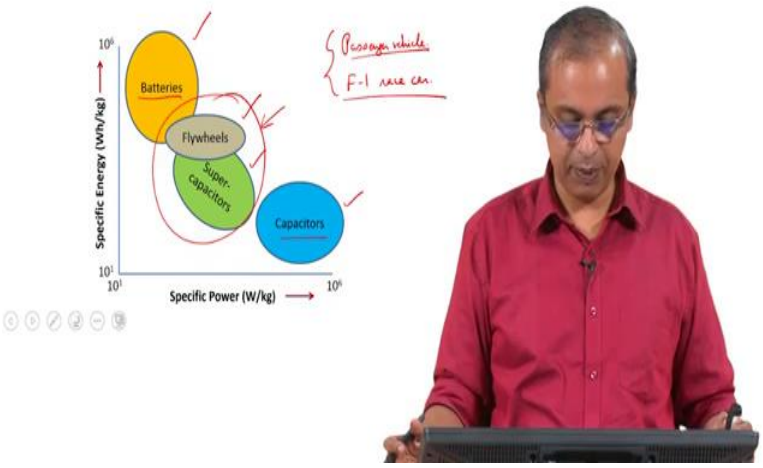

So, if you look at the scheme of where the flywheels fit into the you know energy storage realm of energy storage devices, you can see here we discussed when we spoke about super capacitors and I have you know built on that same image here. So, capacitors will give you high specific power, but low specific energy. And the opposite end of the spectrum is battery which gives you high specific energy, but low specific power. These super capacitors and flywheels come in the middle and in this context the flywheels give a little bit better specific energy, because you know it is there in it is rotating it is able to hold up that energy for a little longer and so on.

So, it gives you a little better specific energy relatively, but it's roughly in the same realm of existence as a super capacitor. So, a flywheel just the way a super capacitor

behaves, a flywheel is also something that bridges the gap between a regular capacitor in the battery.

So,. So, these two energy storage devices that will give a lot of flexibility when you put together you know set of equipment that have to come together to run an electric vehicle. So, you have an application as I said you know the application will have a power demand profile, that has a very specific shape or even a shape that is unpredictable and the power supply infrastructure which consists of a battery of flywheel a super capacitor a capacitor some combination of that, we shall be which you have to design, you have to think of what is the right kind of combination what should be the sizing of the flywheel, what should be the sizing of the battery, what should be the sizing of the super capacitor what should be the sizing of the capacitor.

That is a decision that you as a you know designer of an electric vehicle would have to take into would have to make and then once you make that decision, you and and I will also point out, but there is no single answer for this it is not like there is a if I if one person makes an electric vehicle and another person makes an electric vehicle, both of them even if they did all their calculations both of them are not going to come to exactly the same answer.

The reason being we will each of us will have a different idea of what our vehicle should do. So in fact, even today if you look at you know even if you are looking at non electric vehicles, we are just looking at regular you know passenger vehicles based on petrol running on petrol or diesel; already the modern day vehicles have different settings. They have a eco setting, they have a sports setting and different settings are there. So, what is the difference? That setting simply changes the manner in which the power is extracted from the engine the conditions under which the engine is operating they say the fuel air ratio that is going into the engine.

So, you can optimize the engine to do different things, you can opt if similarly you can optimize the electric vehicle to do different things, you can put an electric vehicle for racing you can put an electric vehicle in an F-1 circuit f one racing circuit. So, there your optimization is for power, power and torque those are the things that you are optimizing for. On the other hand you may want a mass market electric vehicle, which you want to

put on the roads where everybody is going to use it and our intention is to make it as fuel economical as possible there clearly your optimization is going to be very different.

So, in both these cases these two extremes that I am talking off. So, passenger vehicle and an F-1 race car. If both of these you are trying to implement using electric vehicles your choice of battery your choice of a flywheel or super capacitor or a capacitor that combination; however, what capacity what sizing and what material you will use and also what will be the logic based on which you will decide which is going to provide the power, which is going to charge, which is going to discharge, how much it is going to discharge all of that will vary based on what is your requirement okay and that is something that you will have to over decide on. So, this is something that you should keep in mind.

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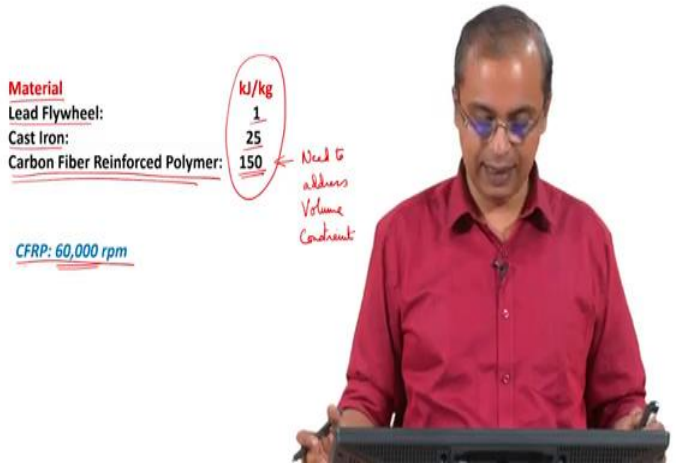

So, I will sort of wind up by telling you a few things about the materials here. So, you can use various kinds of materials for the flywheels, and some of the older toys typically apparently have used to lead based flywheels. So, you can see that it's kilojoules per kilogram it is kind of low it is only one kilo joule per kilogram whereas, cast iron can go up an order of magnitude to about 25 kilo joules per kilogram and carbon fiber reinforced polymers can go up to 150 kilo joules per kilo gram. So, clearly carbon fiber reinforced polymers can hold much more energy per kilogram related to say cast iron or lead based flywheels.

But the only issue is that the carbon fiber reinforced polymer is a very low density material. So, normally this also means the size of the wheel is large the size of the wheel is large. So, if you have volume constraints. So, if you have volume constraints, which is what you are going to have if you are talking of an electric vehicle then this is something that you have to be careful about you have to think about when you implement ok. So, that is something and just to give you an idea in terms of rpm. So, for example, this carbon fiber reinforced polymer based flywheels can go up to 60,000 rpm this is a extremely high rpm so to speak, and these days people are even looking to see if they can get 100000 rpm and so on.

So, very high rpms are being looked at and that is why you should you know remember that you know that can really shatter the material and you have to be kind of careful about it and incidentally these are all also I will also point out that you know in if you want to compare this against conventional things like gasoline, these are all very small numbers. So, gasoline the amount of energy per kilogram it could easily be say two orders of magnitude higher than this. So, that's the kind of number that we are looking at, and so, this is much smaller energy density, but it gives you a lot of flexibility a lot of clean energy so to speak.

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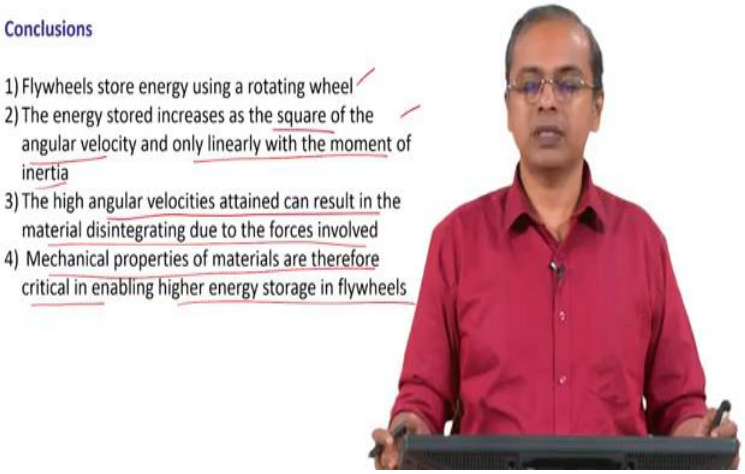

So, in conclusion flywheels store energy you see using a rotating wheel, the energy stored increases as the square of the angular velocity, but only linearly with the moment

of inertia. So, that is the point that we have to remember it is the square of the velocity and only linearly with mass of the wheel so to speak.

High angular velocities attained can result in the material disintegrating due to forces involved. So, therefore, you have to pick the right kind of material, you have to ensure that your device does not cross the threshold of that material. So, during it's operating conditions, there must be some safety feature which ensures that if you reach some rpm, you will no longer be putting energy into that flywheel.

So, something like that you have to have and you also have to have some failsafe mechanism, where in the event that it disintegrates the wheel is contained in some region. So, the parts are contained in some region and mechanical properties of the materials are therefore, very critical in enabling higher energy storage in flywheels, you have to ensure that it has high tensile strength. So, that it doesn't you know disintegrate when it is being operated at high rpms ok.

So, that's our discussion on fly wheels, it is a very interesting form of energy storage and as I said you know in the grand scheme of looking at non conventional sources of energy and how you will utilize that on the road in real life assisting us both serve our purposes, but also to do so, in a clean manner, flywheels also will play an important role. So, with that we conclude this class.

Thank you.

KEYWORDS:

Flywheels; Mechanical Energy Storage Device; Applications of Flywheel; Smoothening of Power output; Regenerative Breaking; Gears; Hoop Stress

LECTURE:

Flywheels and their working principle and its role as an energy storage device is explained .