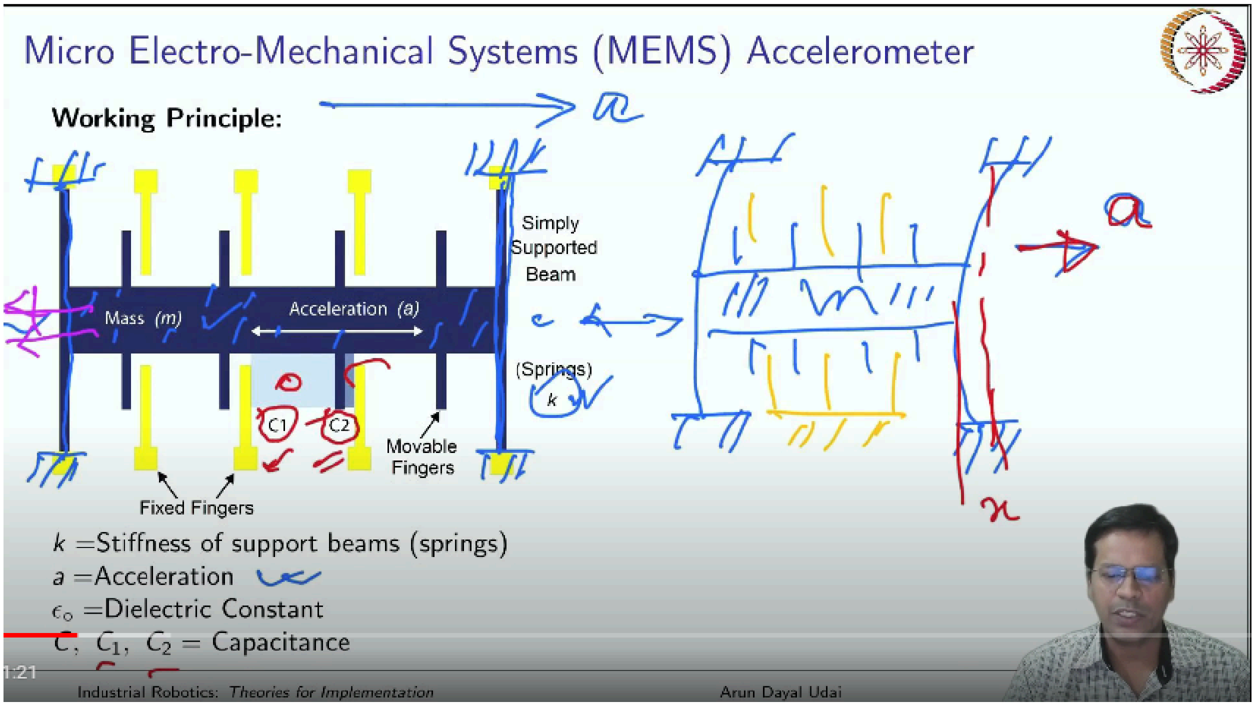
NPTEL Online Certification Courses
Industrial Robotics: Theories for Implementation
Dr Arun Dayal Udai
Department of Mechanical Engineering
Indian Institute of Technology (ISM) Dhanbad
Week: 03
Lecture: 13

Acceleration Sensors, AC Sensors (Resolvers and Synchros)

Welcome back. So, in the last class, we discussed potentiometers. Potentiometer as an angle sensor, we studied, and then we also saw how the Hall effect sensor works. It is a very versatile sensor, you know now. It can be used like a digital sensor for detecting proximity, or it can also be used as an analogue sensor, like the example that I gave you, where it can be used like a tilt sensor. We also saw how to obtain velocity using a potentiometer, which is an analogue output sensor, and using a standard quadrature encoder, which is digital in nature, and you can get the number of counts per second. You can express it as velocity. You saw how a tachometer can be used as a velocity sensor or a dedicated encoder interface, which is a device industrial device which can take input from optical encoders and incremental encoders, and it can give you velocity automatically. So these are a few that we learnt in the last class: going, moving along sensors. So, today, further, now that you are already familiar with obtaining velocity.
Let us see, if you can obtain acceleration also. So, we will discuss acceleration sensors today, especially MEMS-type sensors, microelectromechanical system and AC-based sensors, and alternative current-based sensors, especially resolvers and synchros.

So yes, let us move ahead. So, the acceleration sensor is basically MEMS-based and uses a force sensor. Also, I will tell you how it can be used. A force sensor can be used as an acceleration sensor.

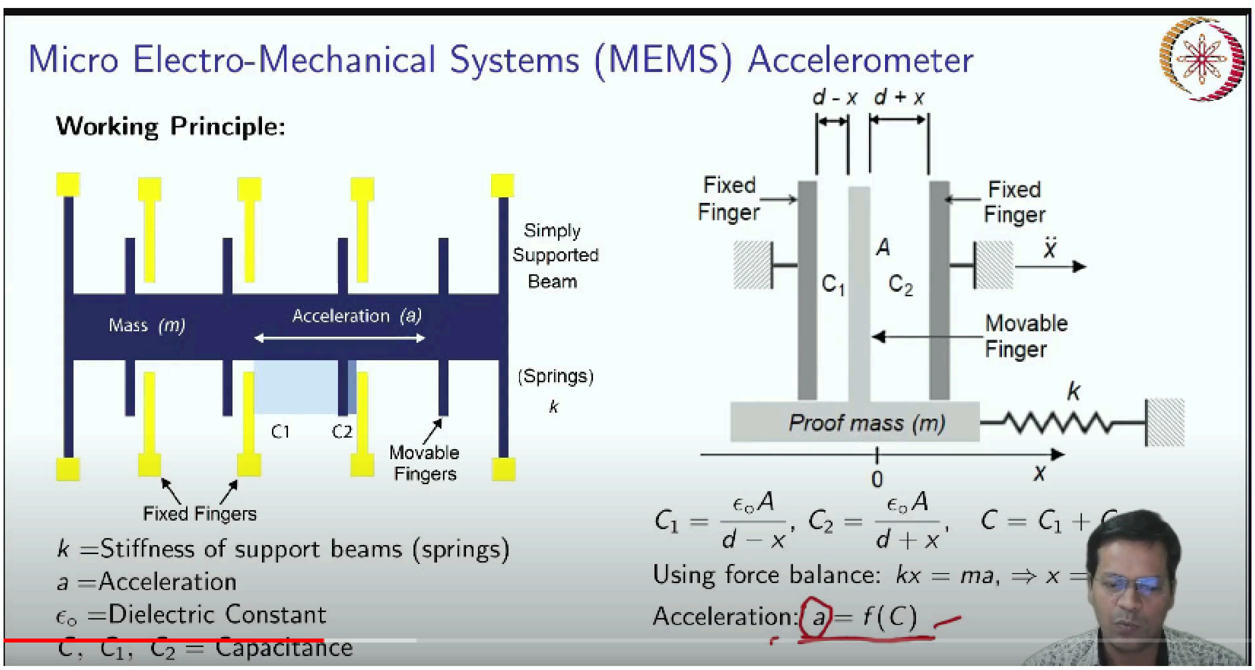


So, here is the basic principle of a standard MEMS accelerometer. So, it is a basic physics. I tell you how it is. So, yes, this is a comb drive, which is commonly known as a comb drive when you have a suspended mass that is blue over here. This is a suspended mass which is floating in its space. It is a free space where it can move can oscillate, and it is supported by a beam-like structure over here. So, It has the beam on which the whole of this mass is hanging. There are two beams which are fixed here, So, I hope you can understand the structure: a mass which is suspended like a simply supported beam at two ends, and it can oscillate. If you give a longitudinal oscillation like this, it will oscillate. So, these are like springs. These are like springs with a stiffness scale, let us say. This is proof mass. This mass is known as proof mass, so this is of mass m, let us say.

Now have some structure which is permanently mounted on the ground. So, these yellow ones are permanently mounted structures which is on the ground, not on the ground. Actually, that also is made up of silicon wafer cut out. So, a part of a silicon wafer remains on the surface that is not moving, and the other part is suspended on a simply supported beam. So, yes, overall this structure is like a comb drive, where you have two different combs which are inserted one into the other and that can oscillate. So, one of them is stationary. The other one can move. It is a floating structure. So, the stiffness of this structure, the floating structure on which it is hanging, is simply supported hang is k. a is the acceleration. Let us say I give to the whole of the system. The whole of the system, let us say it, moves by acceleration a. So, in that case, the mass blue in colour will experience a force which is like this. It will experience a force which is like this. So that is a pseudo force that it can see, and that will tend to bend this simply supported beam.

So, the mass new structure will be something like this: This is your mass m. this was initially hung like this. So now, when the whole of this structure is moving with an acceleration a. this is the situation. So, this whole of the comb drive, which was there along, that also moves. So there were some intermediate fingers which are inserted here, but they are stationary. They are stationary. They are not moving. So what is moving is this blue one which is here. So now, how it is constructed, you see carefully. So you have two capacitors, which are made out of it. One of them is here, that is between the yellow ones, these fingers, fixed fingers- and the moving fingers. So this is the space which is behaving like a capacitor.

You have yet another capacitor which is hanging here, that is C2. This space is also for the capacitor. So, it behaves like a parallel plate capacitor with dielectric in between. Dielectric is air here, so it is epsilon 0, which is here. So, there are two capacitances: C1 and C2. Now, when this has moved, when this has moved due to an acceleration a by certain distance x from the mean position us say it has moved by a distance x, then the capacitance of both the parallel plate capacitors changes. So, that is what is the basic principle. We have to measure the change in capacitance somehow, and we will come to know what the acceleration is. So, that is how it works.



So, let us move ahead. So this is the scenario here. So let us say you just have two capacitors, Although there are many. One is here. Another one here. Here. Here, all of them are actually added in parallel because they are in a structure. They are like that. They are like a parallel plate capacitor, So many parallel plates which are there. So, yes, this is C1, this is C2. So the initial distance between those two plates, let us say it was D. So when you moved along this direction, moved along this direction by an acceleration a, x double dot. So, this is proof mass has moved by a distance like this. Let us say this was x, so this was x, which it moved behind. So, now the capacitance C1, which was initially C1, was epsilon a by d. Now, d has reduced.

$$C1 = \epsilon_0 a/d$$

You see, this gap has reduced. So, this time, the capacitance is C1, that is, epsilon 0 a by D minus x.

$$C1 = \epsilon_0 a/d-x$$

And for the second one, which is here, the initial capacitance again for also was epsilon 0 a by D.

$$C2 = \epsilon_0 a/d$$

Now, after moving, the distance has increased, and this capacitance has now decreased. So, effective capacitance now is epsilon 0 a by D plus x.

$$C2 = \epsilon_0 a/d+x$$

So, the total capacitance is C, which is equal to C1 plus C2.

$$C = C1+ C2$$

The total capacitance, as I told you, is in parallel, which is seen from some connections which are made outside C is equal to C1 plus C2. So, what happens here? So, using the force balance equation, I can obtain this equation. So, this is the stiffness of this proof: the mass on which it is suspended. So, this is the spring, this was the spring which was here which actually moved like this so that they can go flex. So stiffness is k, so k times x. x is the displacement and is the restoring force. So, what is the pseudo force which is acting due to the acceleration? Is m into a.

$$kx = ma$$

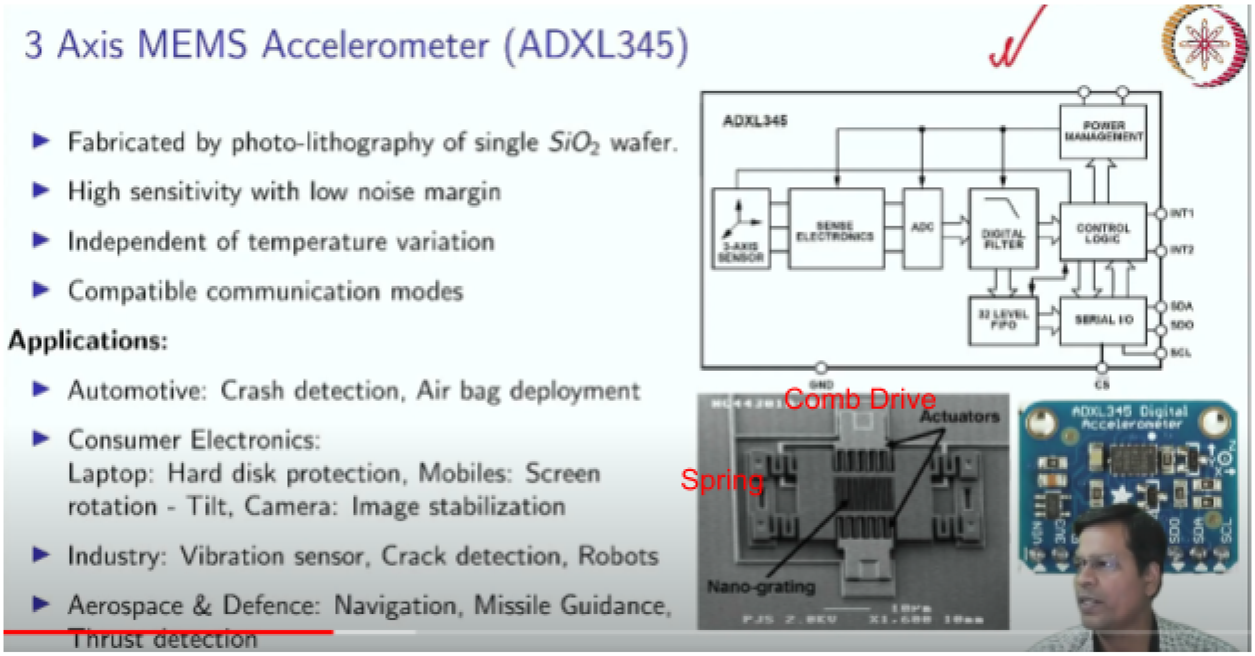
So, this is the equation for forces which are acting on it. They are balanced. So, this is like this. So, ultimately, what you get is displacement x is equal to mass into acceleration by k.

$$x = ma/k$$

That is the stiffness. So, what is constant? x is now a function of ma by k. k is constant, and m is constant, so x is a function of acceleration. So now, if you see, if you substitute that x here in both the equations for C1 and C2, what do you get? You get acceleration as a function of capacitance.

$$A = f(C)$$

So, there is a circuit which actually can detect changes in capacitance. You may just allow AC to flow through a capacitor and just try and measure the impedance. If the impedance is changing, that will change the current which is flowing through it. If you have some pickup which can measure current, you can back calculate how much was my acceleration, because acceleration is now a function of C after doing all this exercise. So, this is how acceleration can be estimated.



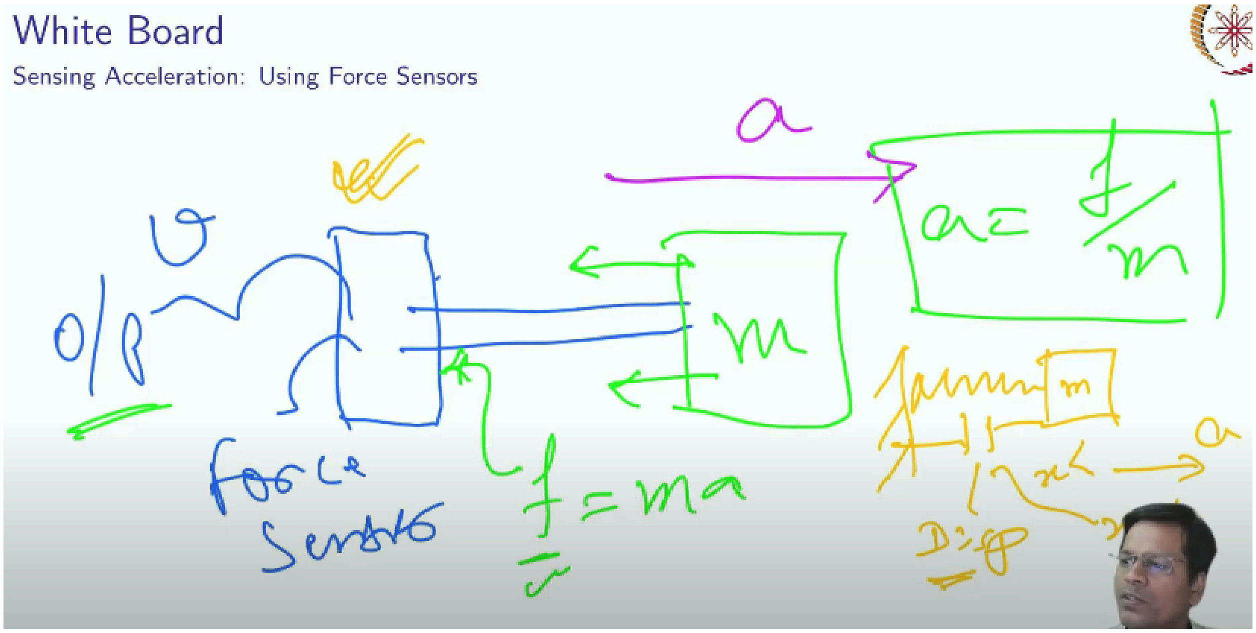
So, what goes behind here is something like the circuit in the above schematic diagram. The circuit, which you are seeing here is of a 3-axis MEMS accelerometer ADXL345, made by analogue devices. I will tell you. First, let us talk about single-axis sensors. So, if this is a sensor, the sensing element is similar to this. So you see how minutely it is constructed using photolithography techniques on a single SiO2 wafer, a silicon wafer. It is fabricated using photolithography. So, you see, these are really tiny ones. So, overall, it is 10 micrometres in size, you can see. So, it is a very, very minute thing, and they are constructed like a spring. You see, It has springs. This is your comb drive, which you can see here. So, this is your comb drive. These are springs. So this small, tiny structure is there. And then this is connected with electronics. So there are some sense electronics, which is here, where you have to measure the change in current or something, any value. Over there, You have an analogue to digital sensor, which is here, circuit ADC is here, which finally converts that signal to analogue value, and then you have filtered to eliminate any noise, which is there, And then you have buffer 32 level, first in, first out buffer, and finally, it is transmitted using serial input and output. It is SDA, SDO, and SCL. If somebody has worked on embedded systems or even Arduino, they know it. Actually, This is I2C, 2-wire interface communication. So, they work like you have a serial clock, you have data, and that is circular.

Buffer kind of thing that keeps on going: input and output. So, that works like this. So, it is master-to-slave communication sometimes, or sometimes it is just one-way communication. Like this device, You just send in the clock, and you can keep reading the data which is there. So, data may be in 8-bit, nine-bit like that, So, normally it is 8-bit. So, if at all you have to read a big value like in 16 bit, then you have to read 2 bytes or something like that. So, that is how it works. So overall, this device is sitting somewhere over here with some external electronics also, and now it is ready to be integrated with some other device like PLC or a microcontroller or a PC or anything like that.

This communication thing can be of various other types, not just I2C. It can just be an analogue output that you can take up in your data acquisition system, and you can read that. So, there are many similar devices which have different conversion things inside. So, that is there. Because it is a sensor, There is a circuit, which is power management, which is here. So, this is how it works. The whole of this comes in a tiny chip. You can imagine what a lot of engineering has gone on here. So, it is very highly sensitive, and it has a low noise margin. So, not much noise it can accommodate. But there are sensors which can measure up to 6G of explorations, 6G, 3G, and 2G. Depending on different types of ADSL devices or this type of accelerometer, you have different capacities.

They are independent of temperature variation. The circuit itself has compensation for temperature. It is compatible with multiple modes of communication. This was I2C. It can be standard, serial, RS-232 or 485. So, there are multiple modes of communication which is supported. There are many applications that you see here, usually for crash detection in the case of a car, which deploys actual airbags tightening your seat belt. Those things are there in case of any accidents in automotive devices, in case of automobiles.

So, consumer electronics like hard disk crash detection, like if at all your hard disk slips off from your hand, it has an automatic feature that it will park its hard disk. Those were the days when there were only hard disks with sectors, cylinders, moving heads and this kind of thing. So, the hard disk is saved that way. So, mobile phones: yes, you have screen rotation, that automatically when you rotate your screen your text is almost straight, always made straight, so that you can view it properly. So, that mechanism is working on a screen rotation mechanism based on the tilt sensor, which is there inside. Camera image stabilisation that works, taking input from this. Industries, you have vibration sensors, crack detection and definitely robots. They make use of this. And in aerospace defence, definitely for navigation purposes, missile guidance, and thrust detection. All these use this type of accelerometer. So, that is all for at least MEMS-based accelerometers, which are very, very sensitive, but sometimes you require measuring huge acceleration. You need to have a very high amount of rigidity in your system. In those cases, you normally use four sensor-based accelerometers. So, what do you have here?

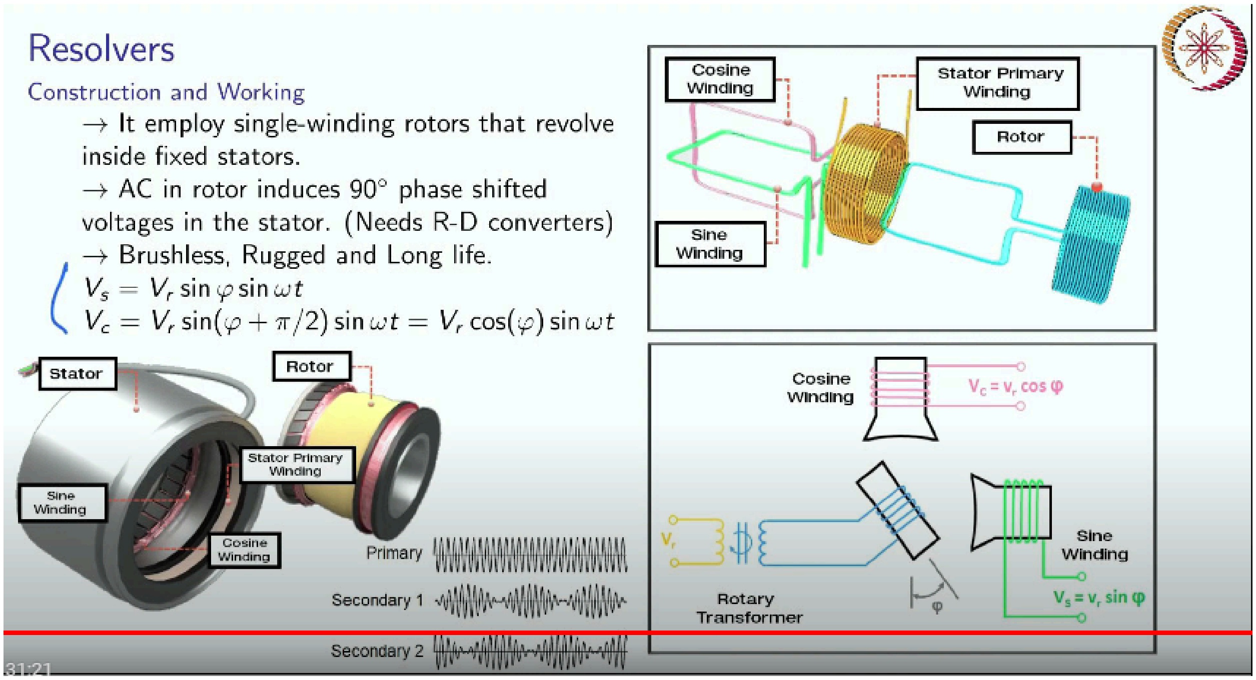


Let us say you have a device which is a force sensor. This is a force sensor. So, it can give you an output in terms of voltage v or anything that has some force coming on here. So let us say this is attached now with a big mass m. This is your mass. So what will happen? Now you got it? What am I going to do? What is there inside this MEMS sensor? I just want to scale it up. If I move with an acceleration in this direction (forward), what will happen? You will experience a force on this mass. This force will be: f is equal to ma (f = ma).

So, this is the force that is actually acting on top of this. So the output lets you know the force, and if you know the force, acceleration is just force upon m.

$$a = f/m$$

So, this is the first principle that can be used. Just use simple physics. You can convert any force sensor to an acceleration sensor. Similar is the case. Let us say you have a spring. In this case you have a spring, you have a mass, and maybe you have a sensor which is here which can measure the displacement. So, this is displacement. So, again, if this is a mass, I make the whole of this mount move with an acceleration a, and this displacement will be reduced. So distance between them, if it is x, x will be reduced. So, using some external device, if you can measure this displacement, you can definitely estimate how much your acceleration is. So yes, there are many ways to measure acceleration using some primary sensor. Over here, I have demonstrated how it can be used using a force sensor or a displacement sensor. You can also have other things which can be used, like an acceleration sensor.



So, let us move ahead with AC devices. So far, the devices we have studied are only DC that use a DC voltage to operate, mostly from 5-volt to 24-volt regions. Nowadays, you see your sports watch have an accelerometer inside So, that can detect the number of skipping you have done pedometer kind of thing. So, all those sensors, they use this. In that case, you see, a simple lithium-ion battery is able to drive it. So yes, now talking about AC devices, it can be for position measurement, or it can directly give you velocity. Two major one of them are resolver and synchro. Resolver is very, very common in industrial motors. I will tell you why.

Let us first understand how it works. So, starting with that. So yes, internally, resolvers are connected like this: They employ a single winding rotor that revolves inside a fixed stator. Just look at this figure carefully. So I will just make myself vanish now so that you can see the figure clearly. So, this is it. So the bottom right corner, So this one, what it is actually, let us say, it has one solenoid coil which is here. It is not supplied by any external supply, and rather, it will just detect what is coming out of the stator armature, which is rotating inside. So, this is your armature, which has a winding, which has a winding. Over here, you see, And this carries an AC signal and this is fed to it. So now, if it rotates, if this rotates like this, what you see at a particular angle, the maximum amount of flux that is coming out of it, will be linked to this coil (cosine winding) and this coil (sine winding). So, if it aligns with the top coil, number 1, this one will see the maximum voltage induced because of AC, which is here. So, the one, if it is aligned, 100%, that is the maximum amplitude of AC that will come here. If it is 90 degrees, if it is like this, this will see 0, like So there won't be any flux which is passing through this. So it will be almost equal to 0 voltage of AC that will be induced here.

So, what about this coil? This is a sinusoidal coil. In this coil, things are a little different. So, this sees the maximum value. When it is aligned like this: Okay, your armature is aligned with This one will see the maximum value (sine winding), whereas this one will go to the minimum value (cosine winding). So you see, there are two picks up coils, which are in the stator. It is fitted. One of them is cosine winding, the other one is sine winding, And the armature carries the AC signal. So, AC is transmitted to this using slip rings or maybe using a transformer, which is here. So, that is contactless in nature. So you have a coil which is like this, you have another coil like this. Both are rotating about its axis, about this axis. This is also rotating, So this coil will induce. If this carries AC, this will also carry an AC signal of the same frequency. Amplitude may be different depending on the flux linkage between them. So, this is how you can transmit AC from one coil to AC on the rotor. So this is your input, So, the output goes to the rotor. So, this is your rotor. AC in the rotor induces 90-degree phase-shifted voltages in the stators. If one of them, the voltage varies as V is equal to V0cos of ɸ. ɸ is the angle which is here.

$$V = V_o\cos\phi$$

Another one will see V is equal to V0 sine of ɸ. Actually, it is cos 90 degrees plus sines. So, that effectively gives you V0 sine ɸ.

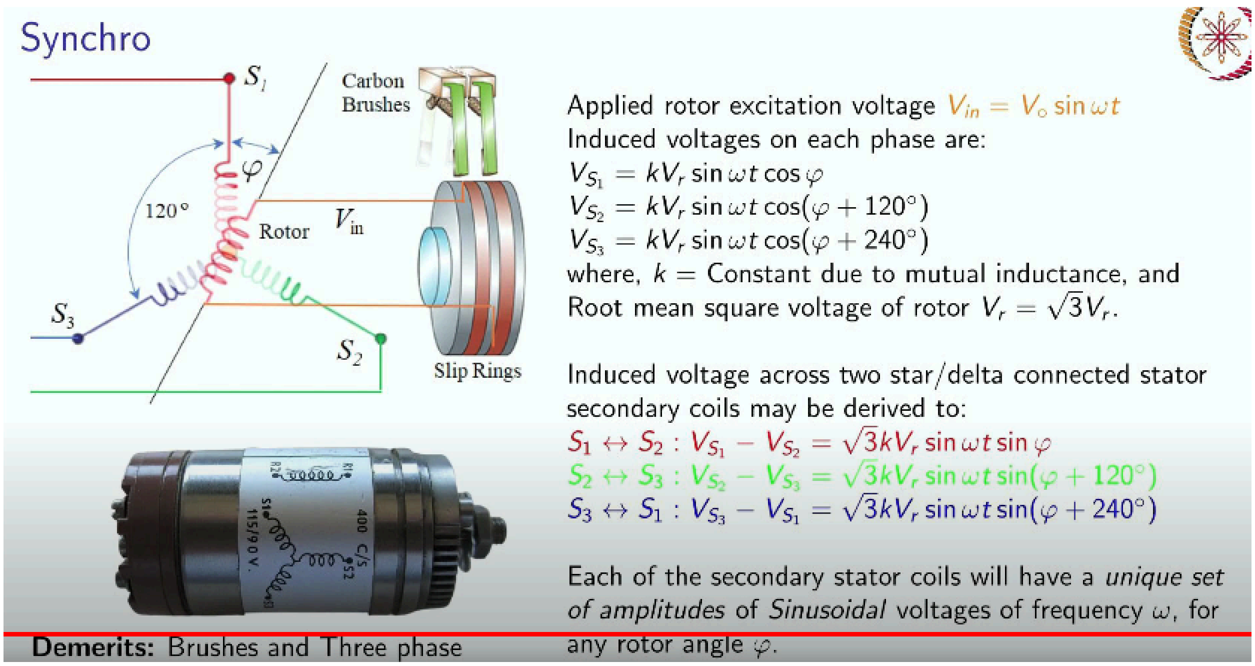
$$V = V_o\sin\phi$$

So, that is what is the voltage that comes here. Both are AC, mind it. So, this (ɸ) psi and AC signal is different. So, the AC signal is V, which is equal to V0. Let us say it is some value, Vmax sine Omega t.

$$V = V_m(\sin\omega t)\cos\phi$$

So, this is the AC signal. So, the output is AC, and due to linkage, it creates a cos of psi that is generated in the cosine coil. So you see, this Omega frequency remains the same in the rotor as well as the stator coils. But what varies is the amplitude. Amplitude itself has got a frequency inside, So, it is a double sinusoidal thing. But this sinusoidal frequency is fixed. The outer one, this cos psi, varies. That depends on the angle, psi. So, what you see here, the secondary one will have a voltage which is induced like this. So, this one is for the sinɸ. So, this is one, and this is for cosine ɸ. So, you see, frequency in both the coil is the same, and in the primary. So, whatever is the frequency that comes from here, that goes here. That goes here. That goes here. So, the frequency remains the same. But the amplitude varies. So, this varying depends on the angle psi (ɸ). So, you have stator-primary, and stator has got two secondaries, Cosine and sine winding. The rotor is there. The rotor has a primary winding. That is there. In the primary winding, it is transferred using the transformer, which is here. Got it? So, that is what it is made up of. And then you see something like this. So, this is yours, and you see this whole of this system. There was no slip ring. You could have transferred electricity to the armature rotating coil using slip rings, but because it is AC, a transformer can replace that, and it makes things brushless. So, that is the reason it has a long life. They are very, very rugged. They can be supplied with the existing power supply, which is already there in your system somewhere. You don't need to convert it, rectify it and then use it. So it is very, very simple and quite rugged. It is used mostly in industrial AC servo motors to detect your angle.

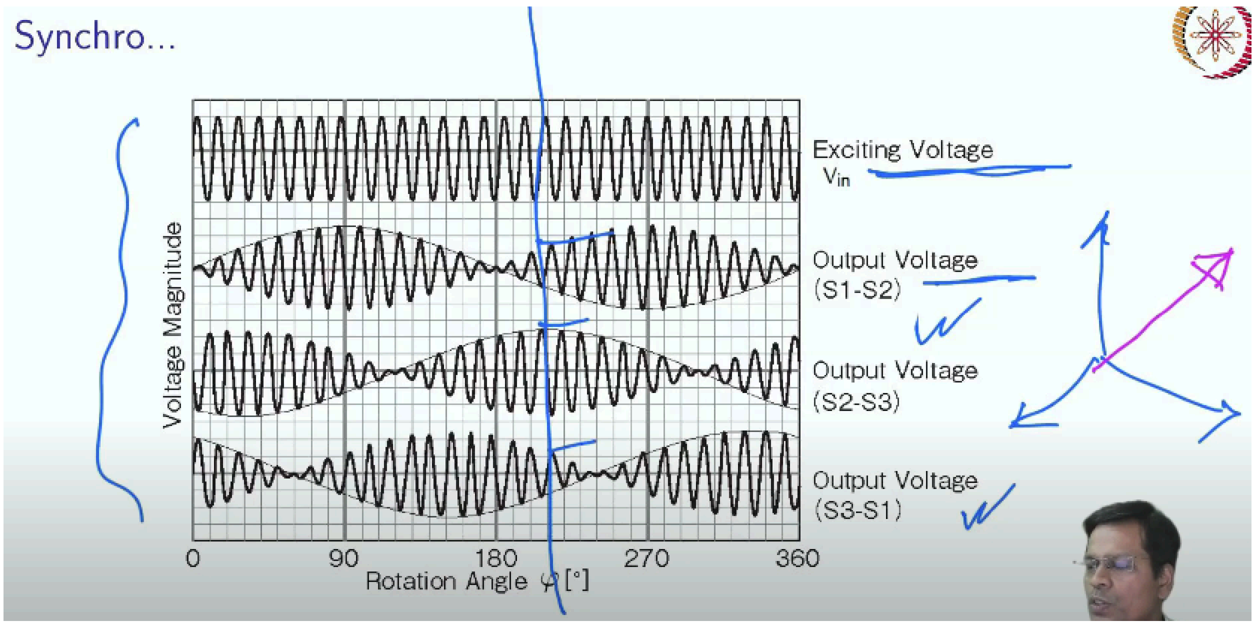
So, the angle can be detected based on any single instance of both coils. Let us say this is the place I am. I am seeing amplitude here and here. So, a vector sum of those two amplitudes in both directions will give you the position of your rotor. So, you just have to measure the amplitude in cosine, amplitude in cosine, and this is sine, and the vector sum of those should give you the direction. So, this is how it works. So, these are the two different waveforms which I have noted here so that you can see a clear picture out of them. So, this is how this resolver works.



Here is a device which is known as a synchro. This is an older device which used actually a simple three-phase system instead of two phases. So, instead of the difference between resolver and synchro is nothing. The only difference is the resolver has two phases, whereas this one is three-phase. So, you now have three different coils which are there. So, your rotor will induce in one of them. Let us say this is the input frequency, omega. So, this is your input one. This is the linkage which is there. Vr is the rotor voltage. Vr sine omega t cos of psi (Φ).

$$Vs1 = kVrSin\omega tCos\Phi$$

So, psi is the angle of the rotor, which is here. So, this is how it is linked. So, if the psi is zero degrees, it will see the maximum amplitude. So, this one number one will see the maximum amplitude when psi is zero degrees. So, this one will see maximum. When size 120 degrees. So, this is how it works. So, the phase difference between all of these is like this: So, 120 degrees. The other one is at 240 degrees. Got it? So yes, I suppose if it is rotating like this can be plus or minus, minus over here. So, this is how it works. So when it is 120 degrees, this will see the maximum one. When this is 240 degrees, it will see the maximum one. It is sine minus 120, sine minus 240. So, k is the constant due to mutual inductance between them, and the root-mean-square voltage square voltage of the rotor is something like this that will be induced. So, it is finally given as this because it is star-connected. So, this difference between the voltages will be transmitted out. So it is given by this, which you can understand. So, yes, this is how it works. So, it is nothing but a little older way because it uses a slip ring. So, it has its own life. You have to change these brushes quite frequently, But, yes, you could have used even a simple transformer over here also, But still it has three wires, which is redundant. Yes, So each of the secondary coils will have a unique set of amplitude in sinusoidal voltages of frequency ω (omega) for any rotor angle sine ϕ (psi), Got it?



So, yes, this is the waveform which is coming out of a standard synchro. So, if this is your exciting voltage, output 1 will be something like this. So if this is a sine a, the next one will be sine a plus 120 degrees. The third one will be sine a plus 240 degrees. Got it. So, this is how all the outputs are. So, at any instant of time, you have 1, 2, or 3 amplitudes. So, you can simply create a vector for all those amplitudes, and finally, what you will get is a rotating vector resultant that rotates. So, you can directly calculate the resultant of all the three differences, and finally, you can calculate the rotor angle. So, this is how it works.

So, that is all for this lecture. So, in the next lecture, I will be discussing proximity sensors, especially inductive and capacitive types, although there are many. But yes, I will have to stick with this in view of time and your syllabus. But yes, these are the most common one which are there in the industry, so I will be discussing them. So, this is an inductive and capacitance-based sensor and other very prime things which are there to do robotic manipulation, sometimes compliant manipulation, sometimes cobalt they use force and torque sensors. This is one very big class of sensor which is there. So, that I will be doing in the next class, that is all.