Course Name: Engine System and Performance
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Lec 18: Actuators in control system: Solenoids, Piezoelectric and Stepper motor

I welcome you all to the session of engine system and performance, and the topic of our today's discussion is the actuators in engine control unit or engine control system. So, in our last few classes, we have talked about or we have discussed about the sensors, the need of a sensor in the electronic control unit. then input to the sensor, output from the sensor, and then we have talked about four different types of important sensors for modern engines. We have also discussed about their operational procedure, hardwares, and then a particular type of sensor, why that sensor is needed for the safety of the engine as well as efficient operation of the engine.

So, in continuation of that, we also should know about another important element for the electronic control unit or engine management system is the actuator. Actuator or actuators are also important components for the electronic control unit of modern engines. What we know from our understanding of sensor is that the output from the sensor is essentially an electrical signal. Now, that signal should be given to the electronic control unit.

And if we try to recall, for example, if we know that the vacuum in the intake manifold is more That would be sensed by the manifold absolute pressure sensor and eventually that information should go to the ECU. Receiving that input, the computer of ECU will give some feedback to the fuel injectors to supply additional amount of fuel so as to have a balance of the air-fuel ratio. Now the question is that information should go to the fuel injection system. That fuel injection system now should be in a position to supply additional amount of fuel.

And that means if it is a signal received from the manifold air pressure sensor, that signal will be received by the ECU, and ECU will eventually give some feedback to the fuel injectors, so as to increase the opening area of the fuel needle, which is there in the fuel injector system, so as to increase the path or pathway of flow of fuel, and additional amount of fuel can be discharged. Now, all these things are done by the actuators. So essentially what we can understand now actuators are like sensors are important elements for the electronic control unit. Then from our understanding what we can see that input to the actuators should be an electric signal.

And then what should be the output? We can understand that essentially if it is the example that we took today, for that particular case, if we need to really increase the area or fuel discharging area, certainly fuel needle of the fuel injector has to have some sort of displacement. So mechanical output. So, actuators are important elements for the electronic control unit for the control of air fuel ratio, ignition and EGR that is exhaust gas recirculation.

These are important elements for ECU or engine management system to control what air fuel ratio ignition and EGR is exhaust gas recirculation so then as you can see that output from the actuators are mechanical or thermal output essentially input to the actuators are electrical signal so receiving electrical signals or electrical signal actuators are responsible to have or to produce some output which are mechanical or thermal output typically examples of actuators are electric motor we shall discuss today about this taper motor.

Number two, which is very important, that is solenoids. Number three is piezoelectric. Forcing generators. So, these are the typical actuators. We shall discuss all these today. They are hardware structures, and then we will see how an actuator controls air-fuel ratio, ignition, as well as EGR.

So, let us first look at the schematic depiction that we can see in this schematic. This is the construction and principle of operation of a solenoid. Why solenoid have we taken first for our discussion? Because out of these three different types that we have listed down over here—electric motors, solenoids, and piezoelectric forcing generators. Out of these three, solenoids are mostly used.

This particular type is the most popular type because of its simple design as well as being less expensive. I cannot say that it is inexpensive, but as compared to these two different types, solenoids are simple in their structure and design, as well as their operation is not expensive, less expensive. So, this is the schematic depiction of a solenoid. What we can see from the schematic depiction—say, if we give name, this is (a) and this is (b).

So, what we can see, if we look at the schematic (a), then we can see solenoid is essentially but solenoid has a few components. It consists of a steel frame. So, you can see this is a steel frame, which is ferromagnetic. So, you can see that this is steel frame which is ferromagnetic that is also having another steel material. So, steel solenoid consists of a steel frame which is ferromagnetic that contains another steel element which is known as armature and another connecting rod that we can see and the spring. So, these are the very important elements for this.

Solenoid consists of a hollow steel structure which is ferromagnetic in nature that is shown over this hollow structure having black colored outline. Contains another steel element, which is known as armature and connecting rod and the spring. So, these four, essentially, it is having a hollow steel structure, which is ferromagnetic.

Inside this hollow structure, we have another steel element that is armature. It has a rod and spring. These two are basically these two are mechanical stops.

Now let us discuss about its operational procedure. Since the hollow steel structure is ferromagnetic in nature, the wire is wound over the steel structure. So, wire is wound over the steel structure which is ferromagnetic in nature. it contains another steel element that is armature when we allow current to flow through this wire then it forms a strong electromagnet and the moment when we pass current through this wire which is there which is what we can see from this schematic a strong electromagnetism is formed and that electromagnetic force will try to push the spring and it will have some downward movement that we can see from this schematic deflection (b). Let me repeat once again as I said you that here that a coil of wound around the steel frame this is a steel frame a coil of is wound over the steel frame right or a coil is wound around the steel frame it and this allows this entire part to become a strong electromagnet. So, rather powerful electromagnet when we pass electric current through this wire electrical force will be generated that force will try to create or that enforce the spring to be compressed and causing that rod or this entire element to come down. So downward movement and the force that we can see. So, this is creating a downward movement.

So, basically, if we now discharge the current, if we switch off the current through this coil, then again, there will be no electromagnetic force. Since it is spring loaded, so the natural tendency of that particular element or the spring will try to push it off again or to restore its original position. So, this way, if we give some electrical signal, electrical voltage that is from the sensor, that will now create some additional forcing through the formation of powerful electromagnet and that force will try to compress the spring causing a downward movement of this entire setup.

The moment, kind of switch off or if we do not supply any current to the wire, since it is already spring loaded, natural tendency of the spring will be to again uncompressed. To get uncompressed and the structure in steel frame along with armature will try to come back to its original position so this way we really can control the movement of this assembly if we now somehow connect any mechanism so what we can see from the here. So, I can write one by one a coil is wound around the steel frame forming a powerful electromagnet then that Armature and rod are connected. So, if we go back to this, this armature and rod, these two things are connected to this housing using the spring, through the spring and stay at equilibrium point.

So, this armature and connecting rod, these two parts are connected to the housing through the spring and stay at equilibrium condition when there is no current. So, the armature. and rod are connected to the housing through the spring and stay at equilibrium when there is no current flow through the coil. Now, when there is a current flow through the coil, a magnetic force powerful electromagnetic is formed. So, then a magnetic force rather electromagnetic force will be generated.

That pulls or will pull the armature downward, which is what we have already discussed. When there is—or if we allow current to flow through the coil— Because of this electromagnetism, a strong electromagnetic force will develop—or, be generated—and that force will pull the armature downward, as we can see from the schematic depiction shown here (in B). So, if we now discharge the current—or rather, if we switch off the current— flow through the coil, then, since it is spring-loaded, the natural tendency of the spring—the spring force—will try to restore the original position of the armature. That is the complete cycle. So, when current is cut off, the spring force will push the armature and the rod back to their initial position. So, in this way, we can have one kind of abrupt motion of this rod and armature.

The armature will come down, pushing the rod further downward, and then if we switch off the current, it will again return to its original position. That means we can have an abrupt motion of this entire assembly—that is, the rod and armature. So, what we can see is this abrupt movement, that abrupt movement of the movable element is essentially in the form of a mechanical switching action, such that the solenoid tends to be either at rest or against the mechanical stop.

If we go back to the previous slide, these are again mechanical stops. This is also a mechanical stop. So, if the armature gets—or when the armature is coming down—it will stop over here, and if we switch off the current, it will again return to its original position. So, this abrupt motion is as if the abrupt motion is in the form of mechanical switching between these two locations of the armature.

One is its equilibrium location, when there is no force, so it will be in equilibrium condition. But when there is a force acting on the armature, it would be under compressed condition and will rest on the mechanical stop. This is what we can understand. Now, if we somehow connect any mechanism to this rod, that mechanism will also have corresponding movement as the armature moves between these two locations. So, what you can see is the armature has an abrupt movement between two locations. One is what we have discussed here: the rest, which is the equilibrium condition when there is no force at all.

And when there is a force acting on the armature, it will come down and rest on the stop. If we now have any mechanism connected to the rod, that mechanism will also have motion in tune with the movement of the armature and rod. And if that mechanism is connected to the valve of the fuel injector, or if that mechanism is connected to the valve of exhaust gas recirculation, then by tuning the switch of the solenoid—either allowing current to flow through the coil, which is around the steel frame—we can control the movement of the armature, the mechanism connected to the rod, and ultimately the movement of the valve. This way, we can control the fuel injection time and the exhaust gas recirculation valve.

So, this is all about the solenoid that we have discussed today. As I said, it is simple in design and structure, together with being less expensive—not inexpensive, but relatively affordable—which is very important for this particular type of actuator. Because of these two important aspects, the solenoid is most popular in modern engines for controlling the valves. So, with this, let us now discuss another important type of actuator: the piezoelectric actuator. As we have mentioned in one of the slides before, that is piezoelectric force generators.

That means we can have some force to be or some force to be generated by virtue of the expansion of piezo crystals. So, piezoelectric materials, if we allow current to flow through the piezo crystals or piezoelectric materials, they will expand. And if we now again discharge or if the piezo crystal expands, the crystals discharge current, then again it will come back to its original position. So, by expanding piezo crystals and again bringing them back to their original position, we can have some control. If we can connect another mechanism to the piezo crystals, then in tune with the movement or expansion and compression of the piezo crystals, that mechanism will also have some linear motion. So, in the first case solenoid is basically a a type of actuator wherein an electrical signal is converted to linear motion.

So, I forgot to write that solenoids convert electrical energy to linear motion—that is very important. So now, let us look into this particular type, which is the piezoelectric actuator. As I said, this particular hardware—we can see the construction features of this particular type of actuator. This particular type is becoming more popular in fuel injection systems. The fuel injection system is basically, one multinational company is Bosch. So, because of the series production of Bosch's common rail system way back in 2003. This type of actuator, I mean, became very popular for fuel injectors.

So, with the introduction of Bosch's third-generation common rail system way back in 2003, piezoelectric system became more popular in fuel injection systems. So, from the name itself, you can understand that this particular type of actuator uses piezo crystals. So, what you can see. From this particular schematic depiction, piezo crystals are stacked vertically to form this cylindrical-shaped piezo actuators.

The piezo crystals have a specific property. So, that piezo crystals have an important property of expanding in an electric field. That is very important and piezoelectric actuators work on this principle.

Piezo crystals, if we go back to the previous slide, piezo crystals have a certain amount of thickness. These crystals are stacked together to form this vertical or cylindrical shape. They are stacked vertically. They are stacked together vertically to form the cylindrical-shaped piezoelectric actuators, and these piezo crystals have a very important property: they expand in an electric field. Now, let us discuss another important aspect of this particular type of actuator. So, as I said, this piezoelectric actuator, work by passing electrical current through piezoelectric crystals, or through a stack of piezo crystals, causing them to expand.

Next is as the current or the as the piezo crystal discharge current, it contracts or, the piezo crystals contract to the original size. So, these two are very important. Piezo crystals have an important property that when an electric current is allowed to pass through those crystals, they expand. So, that means they have an important property of expanding in an electric field.

From the schematic depiction that we have discussed in the previous class, a few piezo crystals are stacked together vertically to form this type of actuator. If we now allow electric current to pass through these crystals, they will expand, causing them to, have some linear kind of movement as the piezo crystals are expanding. So, the entire stack will have some linear movement, and when the crystals discharge current, all these crystals will return to their original size. So, that means if we now go back to the previous slide, if you can see this needle, so this needle is now connected to this piezo crystal. A few crystals are stacked vertically to form this actuator. If we allow now current to flow, they will expand. They will create, as they are expanding, some downward force on this needle, and the needle will come down. If the needle comes down, then you can see that this area through which fuel will flow from, this kind of nozzle pressurized fuel from the nozzle.

So, fuel is coming from the nozzle from the fuel tank, and it is getting stored over here. Now, if the nozzle is always remaining seated over here, and that needle is always getting seated, if we somehow can create some force on the needle and if the needle is having downward movement, then we can control the opening area through which fuel will flow from this device into the engine cylinder. So that means by passing the current or tuning the magnitude of current, we can have the linear movement of the needle as the crystals are expanding. So, this expansion will create some thrust or force on the needle. The needle will have downward movement, which in turn will allow the opening area through which fuel will flow.

And we can control the fuel to be introduced into the engine cylinder. So, this is how this particular system works. Now, typically for any fuel-injected engine, that fuel flow, characteristics should be rectangular flow type. Now, the question you should know is that the piezo crystals are having almost negligible mass. So, because of this low inertia, typical time to open and close this needle. So, that means the piezo crystals are having almost negligible mass—I should say negligible mass. Inertia is less, so by passing current, if the crystals are having significant or, high mass, then what will happen? The inertia will not allow them to expand, and that inertia will not allow the needle to come down.

So, because of this negligible mass of the crystal, inertia is less. Typically, the time of opening and closing the needle is of the order of 250 milliseconds. And as I said, almost all fuel all engine injection systems are of a particular type of characteristics. So, as I said, the piezo crystals are having negligible mass and thus, the inertial effect due to the involved masses is very less. It is because of this, less than 250 microsecond is needed to switch from the closed position of the needle to its open state. That fueling characteristic of all nozzle or modern engine need a basic requirement, which is rectangular flow filling.

Most engine applications need a specific requirement or specific fueling characteristic that is as close as possible to have to a rectangular flow function. What does it mean? So, if I underline this keywords that most of the most engine applications need a specific fueling requirement or characteristic that is as close as possible to a rectangular flow function what does it mean. That mean the if i go back to the previous slide wherein we can see the schematic depiction, so the moment natural tendency of the needle should be to remain seated over there allowing the passage through which flow can flow should be totally blocked so that means the needle will always block the flow passage area that is passage area of fuel flow. If we now allow electric current to flow through the piezo crystals, piezo crystals will expand and this expansion process will create a forcing on the needle will come down and again open the area or open the pathway through which fuel will be discharged into the engine cylinder.

Depending on the amount of electricity we are passing, we can control this opening area. Now, so we need certain switching on time and switching off time. Switching on, switching off. Though the switching on and switching off time is less for this particular arrangement because of low inertia, because the involved mass or involved masses has low inertia for this particular arrangement, typically less than 250 microsecond. So, it is having rectangular flow function.

That means if we show here, time and fuel flow, if we switch on, then it will take less time than continuous flow. Then again, less time, and it will be again like this. So, this is rectangular flow function. So, if we start from here, at zero time, then it will take less time—the opening time switching—and then it will be almost rectangular. So almost constant flow rate for a certain period of time, then again switching off, and then like this. So, this is what is called a rectangular flow function. That is what we have discussed. So, this particular feature, that is the rectangular flow function, is achieved almost in all piezoelectric actuators. So now, finally, we shall discuss this stepper motor.

We have discussed three different types of actuators. One is an electric motor, a stepper motor, then solenoids, and then piezoelectric actuators. So, we have already discussed solenoids and piezoelectric actuators. Now we will discuss the stepper motor. This is again very simple.

So, a few important salient points of this particular type of actuator: What are those salient points? A stepper motor is a brushless synchronous electric motor. So, this is number one important salient feature. A stepper motor converts digital pulses into mechanical or, I should write, digital pulses into mechanical step rotation.

So, essentially, a stepper motor is a brushless synchronous electric motor. So, if we give some input that is a digital pulse, then this stepper motor will have mechanical rotation. So, if there is rotation, there will be revolution. So, basically, one revolution, two revolutions, three revolutions, like this. So, basically each revolution of the stepper motor will rotate, so we will have a certain RPM. So, each revolution of the stepper motor is divided into a discrete number of steps (typically 200), and then the stepper motor must be sent a separate pulse for each step.

A separate pulse, that is a digital pulse, for each step. Basically, then the stepper motor can take a single pulse at a time or only one step at a time. Stepper motor can only take one step at a time and each step of the same size. So, if we have 200 steps, then each step of the same size and stepper motor can take only one step at a time. That is important for this. Now, if we go back, the stepper motor on receiving pulse rotates through a precise angle right typically 1.8 degree. So, since the stepper motor can have a precise rotation of 1.8 degree, we have if the engine is having stepper motor, this can have precise control without any feedback. The motor position can be controlled without any feedback mechanism. So, if we now go back to the previous slide so what we can see that a stepper motor which is again a brushless synchronous electric motor used as an actuator. So, let us discuss about the operational procedure. A stepper motor can convert digital pulses into mechanical shaft rotation.

So, it will rotate. So ultimately if we have input digital pulses, stepper motor can rotate the shaft or can have mechanical rotation by receiving digital pulse. So, as it is motor, it will be having certain revolution. Each revolution of the stepper motor is divided into discrete number of steps, which is typically 200. But each step, the motor can take a single step at a time and each step of same size.

Then if we have some digital pulses, if we have input, then it will rotate. And since, this is very important characteristics that single step it can take at a time and each step of same size, the stepper motor on receiving pulses can rotate through a precise angle of 1.8

degree. And it is because of this only, the motor position can be controlled without having any feedback mechanism. So, now, if we go back to the previous slide, so what we can see?

This is hardware. We have stator cap, output shaft, it will be having some rotation. So, coil B, coil A. And if we have some digital pulses, then it will have some mechanical rotation.

Since mechanical rotation can be divided into discrete number of stages. And that too motor has an important characteristic that it can take only one step at a time and each step of same size. The motor can rotate through a very small or precise angle that is 1.8 degree. And it is because of this we can have motor position control without receiving any feedback mechanism. Now, the question is, since the rotation of the motor is function of proportional to the frequency of the pulses, if we have more pulses, then perhaps that rotation, stepper motor that is, stepwise rotation can be converted to continuous type rotation.

So, this is what is important. So, as I said, if the frequency of digital pulses increases, If the frequency—so essentially, this motor works on the principle that it needs digital pulses. So, if the frequency of the digital pulses increases, the stepper or step movement—the name 'stepper' comes from this stepwise movement. So, the step movement will become continuous, and the motor's rotation will be a function of, or directly proportional to, the pulse frequency.

So, to summarize today's class, we discussed actuators—why they are needed for the engine control unit and the different types used in modern engines. Then, we discussed three important types of actuators. One is the solenoid, which is widely used due to its simple structure and inexpensive components. Next, we discussed the piezoelectric actuator, commonly used in fuel injection systems. Finally, we covered the stepper motor. The solenoid is an actuator that converts electrical signals into linear motion. With this, I conclude today's session, and we will continue our discussion in the next class.

Thank you.