Course Name: Engine System and Performance
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Lec14: Description of Electronic Control Unit (ECU) and types of control system: Open-loop & Close loop

I welcome you all to this session on engine systems and performance. Today, we shall discuss different types of control systems. If you recall, in the previous class, we discussed the engine management system, also known as the electronic control unit, and we have seen that the sole objective of this system is to coordinate the functionalities of several subsystems, essentially to increase engine performance at reduced emission levels while ensuring engine safety. We have seen that there are several, basic objectives like fuel injection control, spark advancement control, emission control, and speed control—all monitored by the engine management system or electronic control unit.

This control is achieved with the help of a few sensors. The question is, if those sensors start malfunctioning, what will be the consequences? The ECU is equipped with a few sensors. Upon receiving signals, those sensors send out electric or voltage signal outputs.

The question is, there is a high chance that after a few cycles or days of operation, a sensor might start malfunctioning. In such cases, adequate arrangements should be in place within the ECU to ensure the safe operation of the engine. So, to account for this abnormality— where sensors might start malfunctioning—there are additional functionalities in the electronic control unit, which we listed in the previous class.

One such functionality was the replacement of default signals or default values of faulty generated from the temperature sensor. The temperature sensor—that means, though we did not discuss this using a schematic depiction, we shall discuss that aspect today. But temperature sensors are typically ambient air sensors, which are, integrated with the intake manifold, and the cooling water jacket also has a temperature sensor.

So now, sensing the temperature of both the cooling water—the temperature of the coolant in the cooling water jacket—and also sensing the temperature of the air which will be drawn into the engine cylinder, the ECU controls or adjusts because the mass flow rate of air depends on what?

$$\dot{m}_a = \rho_i v_s \eta_v$$

This is ρ_i. So, that is the density of the air which will be drawn into the engine cylinder. So, this is volumetric efficiency, and this is swept volume, and this is essentially

$$\rho_i = \frac{P_i}{RT_i}$$

So, if we can monitor the temperature of ambient air, we can also control the mass flow rate of air that should be drawn into the engine cylinder because this is directly related to the efficiency of the engine.

So, what does it mean? So, sensors—that is, cooling water temperature and ambient air temperature sensors—should also be functional always. But as I said, there might be a situation when the temperature sensor will not function properly. In such a case, adequate preventive measures will be taken by the ECU or engine management system, and that alternative arrangement is the replacement of default values of faulty signals from the temperature sensor. Typically, temperature sensors are located in the intake manifold and in the cooling water jacket.

So, what ECU does, if sensor fails engine controls unit or electronic control units should be able to run the engine without inviting additional problem. So, by how it does? It substitutes. If temperature sensor fails, it substitutes a fixed value for that sensor input.

Sends out a faulty signal and continues to monitor the sensor if or continue to monitor the incorrect sensor input. So what ECU does if a particular sensor starts malfunctioning. ECU will be having adequate arrangement or adequate functionality, so that ECU will be able to substitute a fixed value of that sensor's input and then send out a fault code and continues to monitor the incorrect sensor input. If sensor's resumes or returns to its normal activity then again engine will return to its normal activities. So, that is what we have discussed in the last class.

So, I discussed that one of the functionalities is to replacement of the default value of voltage signal generated from the temperature sensor. So, this is an important issue. So that is also taken care by the ECU. By how? That is what I have discussed today.

Now with this, let us discuss the replacement of default values for faulty signals. Generated from temperature sensors, typically ambient air and coolant, and this is what is done by the ECU. Today, we have discussed how the ECU or engine management system takes care of it. So, with this, let us discuss a basic control unit. The ECU or engine management system has manifold applications, essentially to maintain or control fuel injection.

To control spark advancement, to control emissions, to control speed, and many more. Now, this is a basic schematic definition. I will try to describe the functionality of the ECU using this example. So, what you can see from this example is, that this is the engine cylinder and this is the cooling water jacket has a sensor.

The temperature sensor, which is connected to the ECU. Now, the question is, when the ECU receives an input signal, the ECU will receive an input signal from this temperature sensor and then will send some feedback. So, pressure and temperature—you can see these are the inputs because they are directly related to the mass flow rate of incoming air. This pressure sensor and temperature sensor are connected to the intake manifold, and also, this is a sensor used to control the throttle opening area.

Throttle valve adjustment and this is another sensor which controls the speed of the engine. So, this is N, which is, so P and T, these two sensors are input signals. The P and T signals from the sensors are integrated into the intake manifold. Now, if we go back to the previous slide, we have written here that temperature is very important to be monitored continuously.

The pressure of the ambient air should be monitored continuously to ensure that the proper amount of mass flow rate or the proper amount of air is drawn into the engine cylinder. If the airflow or intake air, or the amount of air drawn into the engine cylinder, is not at par with the theoretically calculated value, then it will have detrimental consequences. Combustion may not be complete or efficient, and the exhaust gas that comes out will be either rich in oxygen, which will also have overhead, leading the catalytic converter to run beyond its optimum efficiency, and most importantly, the power output will be less. So, this is very important. By receiving signals from these two sensors, the ECU will adjust, generate some output, and provide input to the throttle valve.

If temperature and pressure inputs go to the ECU, knowing the exact input, the ECU will try to give an output signal to the throttle valve so that, if necessary, the throttle valve opening area can be adjusted. This ensures an adequate amount of air is drawn into the engine cylinder. Similarly, for example, if the RPM, which is the speed of the engine, decelerates or accelerates from its normal condition, then the engine will signal the throttle valve to open or control its opening area. This essentially adjusts the amount of air or air-fuel mixture drawn into the engine cylinder. So, this is one thing.

Now, the question is, if it is an SI engine, then certainly the air-fuel mixture should be controlled. If it is a CI engine or even for modern SI engines. In most cases, fuel is sprayed into the engine cylinder via a multi-port fuel injection system. So, what will happen is, that after receiving signals from the speed control, or the speed sensor, the ECU will provide a signal to the pump, which will deliver fuel from the fuel reservoir into the fuel nozzle. So, this is the fuel nozzle.

Now, you can see that the fuel pump receives, or takes fuel from the fuel reservoir and then pumps it. That pump is responsible for delivering fuel through the fuel filter and the fuel pressure regulator into the fuel injector. Now, for any reason, if we need to supply more fuel or restrict the amount of fuel delivered by the fuel injector. What it does is? The ECU sends a signal to the pump, the fuel pressure regulator, or the fuel pump, and also through the throttle opening area. The pump will always deliver a certain amount of fuel. Now, if that amount of fuel is not needed by the engine at any particular instant, then that information will be provided by the ECU to the fuel pressure regulator, and the excess fuel will be returned to the fuel reservoir.

So, this electronic control unit, which is a centralized system used to monitor the activities of several subsystems, has made a significant contribution to reduced fuel emissions and improved efficiency. So, this is what we have discussed about the fuel injection system. It is not just the fuel injection system, as I told you, even if it is the temperature sensor attached to the cooling water jacket receives a signal indicating high cooling water temperature, then that means combustion is increasing, or the fuel-air ratio is either lean or rich.

So, that means the engine sensor temperature. The cooling temperature sensor, which is attached to the cooling water jacket, will provide a range for the optimal operation of the engine. Now, if the temperature recorded by that sensor exceeds that value, then the ECU will take preventive measures to control the combustion rate. This, in turn, will ensure the temperature of the cylinder wall and the piston face remains under control. So, this is essentially a schematic depiction of an ECU or engine management system, illustrating its functionalities.

This is not all; there are many other sensors. Though I have tried to represent everything using this block diagram, in reality, it is very complex. As I mentioned, the speed sensor measures the engine's RPM. If the RPM decreases or increases, the ECU will adjust the throttle opening area or the fuel supply to maintain the engine's speed at its design value. So, with this, let us now move on to discuss control systems.

Today, our focus is to discuss different types of control systems. Before classifying different types of control systems, let us discuss what control theory is? So, control theory. Any control system will work based on control theory. Without understanding control theory, no one can design a control system.

So, whenever someone is trying to design a control system like an electronic control unit, it should be based on control theory. So, what is control theory pertaining to the discussion we are having today? Control theory is a branch of engineering and mathematics that deals with how to control a system or how to control systems to obtain a desired output. So, this is control theory. Any control system is reliant on control theory.

Violating control theory, no control system can be designed, and forget about the working capability of any control system. So, now, this is control theory, but we shall discuss control systems. So, the system—any system—should be controlled, like an engine system. So, if we need to control the engine system, the system that is being controlled is called a plant. So, basically, if we need to control the engine system, the engine system is known as or is called a plant.

So, let me write here the system. The system which is being controlled is known or called as a plant, and the devices which are used to control the plant or system are known as controllers. So, plant and controllers—these two are important.

So, the system that is being controlled is called the plant, and the devices which are used to control the plant are known as controllers. So, they are known as controllers. There are two different basic types of control systems. What are those?

Two different types: one is an open-loop control system, and the second one is a closed-loop control system, sometimes also known as a feedback control system. So, let us discuss these two systems one by one. So, what is an open-loop control system?

So, if we discuss this control system first, then let me discuss it using the block diagram. Open loop or open type control system. If we try to recall the definition of control theory and then what we have discussed that the system that is being controlled is called plant.

So, we will have a plant which should be under control. So, this is plant. So, if we need to control the plant or control a system, then there we need a few devices. So, if we have the block diagram, so those devices are known as controllers. So, receiving signal, so these are plant input, these controllers will drive the plant.

So, plant will receive some input from the controller, so these inputs are plant inputs. Again, these controllers will receive some input from the environment, from the practical scenario. So, these are some inputs, and controllers will receive some input and based on these inputs controllers will give some inputs to the plant and then we will be getting output or rather system output.

So, this is the block diagram of a simple or open-loop or open-type control system. So, this is the most basic type, and it has the least amount of functionalities that you can see from the block diagram itself. So, what it does essentially for this particular type of control system is the desired output is fed into the plant. So, let me repeat once again: pertaining to this system, a desired output is fed into the plant.

Controllers provide some input to drive the plant to obtain that output. I will try to explain this by taking an example. So, again, I am repeating: this is the most basic type, and from the block diagram itself, you can understand that this particular system has the least functionalities. What does this system do? This system is reliant on an important aspect: the plant is fed, or the desired output is fed into this plant or system.

So, the desired output, sometimes also known as the reference, is fed into the plant. Controllers receive some inputs—whatever may be the input from the environment—the controller will give some input to the plant to drive it, or the controller will drive the plant by providing some inputs, and then the objective would be to get the system output. But the output is always fed into the system. So, this is the basic type, that is, the open-type control system. But you can see this particular type of control system has one important drawback. What is that? It has no provision for receiving feedback.

So, it will certainly give some output because already we had, the plant is given some, reference or desired output. Though the plant will run receiving some input from the inputs from the controller, but essentially output should be that desired output. So, there is no feedback in this control system and it is because of this feedback, the problem of this system is the lack of feedback or if since there is no feedback, system is unable to react to changes in its control. environment condition. So, that means, since there is no provision of decision feedback and it is because of this the system is unable to react to changes in its environment as there is no way of knowing what the plant is actually doing. So, since no feedback, there is no permission of receiving feedback to the plant, there is no way of knowing what the plant is actually doing.

And since there is no way of knowing what the plant is actually doing no matter whatever changes are there in the environment or outside. It will always provide the desired output. In a cruise control system of a car, what is cruise control? Cruise is essentially an electronic device that monitors the throttle opening area so as to maintain a constant speed. So, in a cruise control of a car, that means if the car is having a cruise control, cruise is an electronic device that monitors throttle opening area so as to maintain a constant speed.

So, in a cruise control car, if driver sets the speed of the cars is 50 kilometer per hour. Say for example, that is the desired output. So, driver sets the speed of a car 50 kilometer per hour and that is the output fed into the system, desired output fed into the system. will be there in the environment or outside, plant will not understand. So, because it has no way of knowing what exactly plant is doing.

So, what will be having, say for example, if the car, so long as the car runs on a straight road, it has no problem. The car will be having or car will be able to maintain a constant speed of 50 kilometer per hour. Now, if the car needs to uphill, then certainly it will decelerate. engine speed will reduce and if engine speed reduces so control the electronic control unit or electronic engine management system will be able to provide some feedback to the throttle valve or sensor which is there in the fuel injection system to provide or to supply additional amount of fuel or additional amount of air fuel mixture so as to have more torque will be developed. but that feedback is not there.

Due to the lack of this feedback system, these systems are not used or can be used under certain operating condition only. So, system with the open type or open loop control system cannot be used under certain conditions. We shall discuss those conditions. So, what you can understand that the lack of feedback of this particular system does not allow this particular system to be used under differ in all conditions rather.

ECU is not correcting electronic control unit for this particular type of system is not correcting the air fuel ratio as I said you if the car needs to off-heel certainly it will decelerate so speed would not be 50 kilometer per hour but if we need to maintain the same speed certainly we need to supply additional amount of air fuel mixture to the combustion chamber right that information is not given to the controller because the controller does not know what plant is actually doing. Because the plant is fed with the desired output that is 50 km per hour. So, ECU is not correcting the air fuel mixture or even if sensor of the exhaust gas oxygen sensor, if that sensor even provides some input to the ECU, issue won't be able to correct the air flow mixture.

So, considering this, this particular control system or system with this particular type of control cannot be used in different conditions, and those conditions are: open-type systems are not recommended. For the following conditions. Number 1 is cold start, number 2 is engine starting. Number 3 is medium to heavy load condition. So, if the engine needs to supply medium to heavy load, I should write operation.

So, under these conditions, a system equipped with an open-type control unit is not recommended for these three operations or conditions for any system. So, a system equipped with an open-type control cannot run with full efficiency. Or, without any trouble under these three conditions: engine starting, cold start, and medium to heavy load operation. So, now let us discuss the next one, which is closed-loop control system or feedback control. So, let us discuss this type using a block diagram.

So, we have the plant, and then we have the system output. So, we have the system output. So, this is the system output. Then again, we have plant inputs. The controllers will provide some inputs to the plant, and those are plant inputs. So, this is the controller now. This is very important. So, we have inputs.

Now, this is closed type or closed loop. So, we have rather we should have, we should design this particular type taking the feedback of the environment into account so as to run the engine always with its best performance with reduced emission level so that means there is a provision of taking feedback what plant is doing so as I told you in the previous case controller did not know what plant is actually doing and it is because of this situation or lack of feedback from the plant output, controller will not be able to control the plant output and plant always will give desired output which is already fed into the plant. So, in this case receiving if some sensors will be there.

And sensors will, the sensor will correct or rectify something and this will go here. So measured output, so either are plus. So, this is the measured error. So, I should write using this. So, what we can see from this block diagram except the loop.

So, if I now mark here except this particular loop that is feedback loop. Except for this loop, the block diagram looks like an open type control system. So, what is the speciality of this particular feedback loop? So, as I said you that in open type, it is not possible to receive feedback from from the environment now for this case what we can see or from the schematic deflection we can see that feedback loop allows the system to basically get some signal get some input from the environment so this feedback loop allows the system for changing condition.

Because there are some sensors by utilizing some sensor monitors engine operating conditions. So that means all these inputs we will be receiving like pressure, like temperature, like speed, temperature of cooling water jacket, temperature of ambient air, pressure of ambient air. So, all these inputs are from the engine operating condition. So, and those inputs are provided to the controllers, if needed controllers will adjust and then controllers will give some input to run the plant and will be getting always or will be obtaining always desired output. Now, this feedback loop allows the system for changing condition, allows the system to adjust for changing condition.

So, this feedback loop allows the system to adjust for changing condition by utilizing a few sensors that monitors the engine operating condition like speed, throttle valve location, throttle valve control, and also coolant temperature. So, engine operating condition means speed, coolant temperature, air temperature, and throttle valve position. So these sensors are employed in this feedback loop essentially to monitor the engine operating condition and it is because of this what we can see, if the output is getting deviated from the desired output then the sensors will give some measured output to the input and then either added or subtracted from the measured value that is reference value and then that information is given to the controller and then controller drives the plant giving some input.

So, this is basically the closed type control system. Now what we can see that the provision of this feedback system has made significant contribution to the efficiency and emission level of the engine. By how? So, let us try to discuss this with the help of an example. Rather we can illustrate this particular type of sensor with the help of an example.

So, say if the electronic control unit is responsible for adjusting the air-fuel ratio. Because the air-fuel ratio is essential for proper combustion. If the combustion is proper, the torque generated will be proper, and we will get the proper output. So, if the electronic control unit, which is responsible for providing or supplying the proper air-fuel or correct stoichiometric air-fuel ratio to the engine, then the engine will always run with its designed output. Now, the electronic control unit will receive some signals from the exhaust gas. Oxygen sensor—so, what is the exhaust gas oxygen sensor? Because in the exhaust manifold, there is a sensor, and that sensor is called the exhaust gas oxygen sensor. What it does is sense the concentration level of oxygen in the exhaust gases. Now, that sensor will give some input to the electronic control unit.

For example, if the oxygen level in the exhaust gases is very high or very low, then that information will be received by the electronic control unit, and the electronic control unit will try to adjust the fuel or the fuel injection period. For example, if the oxygen level is higher in the combustion gases, what does it indicate? It indicates that in the air-fuel mixture that was supplied into the engine, the amount of fuel was less, so the combustion was improper, and an excess amount of oxygen comes out with the combustion gases. So then, the ECU will try to monitor that, and the electronic control unit—or the engine management system—will give some output signal to the sensor attached to the fuel injector. The ECU will give an indication to supply more fuel so that the excess amount of air can be combusted with the additional fuel to be supplied.

Now, in any case, if the signal received by the exhaust gas oxygen sensor is such that the oxygen level is very low in the exhaust gases, then that means the fuel was rich in the air-fuel mixture. So again, the ECU will try to give some signal to the intake manifold or throttle valve to supply more air so that the excess fuel can combust with the additional air. Hence, the oxygen level or concentration in the exhaust gases should be optimum in the exhaust gases. So, this is the idea of a closed-loop control system—that means by sensing the oxygen level or oxygen concentration in the combustion gases through the exhaust gas oxygen sensor, the ECU will be able to control either the Fuel injection period or the throttle valve is adjusted to maintain the air-fuel ratio to always be stoichiometric, ensuring combustion is proper.

In such a case, catalytic conversion efficiency will be optimal. So, this is what is very important to know. So, in the former case, we had seen that even when the engine is off-fueling, the speed will reduce, the engine will decelerate, but there is no means, no way of giving that input to the plant or the controller, because the controller doesn't know what the plant is actually doing, right? So, because of the lack of this information, the engine will not be able to attain the desired output.

But for the latter one, that is the closed-loop control system, we had seen that receiving some feedback, allows the system to adjust for changing conditions using this set of sensors to operate the engine or to monitor engine operating conditions. That means either increasing the injection period, fuel injection period, or fuel injection time, or increasing the throttle valve position or opening area so that a stoichiometric air-fuel ratio is always supplied to the engine, and then efficiency will be maximum. Oxygen content in the combustion gases will not be either too high or too low, and catalytic conversion efficiency will also be maximum. So, this is all about these two different types of sensors.

In most cases, in most engines, closed-loop controllers are complemented with feed-forward aspects to certainly improve residence time. Though the electronic control unit is capable of doing all these things, the feedback loop allows even finer control of the entire system.

So, we have discussed two different types of control systems today. But beyond this, control systems can be further classified into two subcategories. That is called one memory-based control and another one is an adaptive control system. So, we shall discuss these two different types in the next class, and with this, I stop here today.