Transducers For Instrumentation
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Lecture - 27
Magnetic Sensors: Hall Measurements

Hello, welcome to the course transducers for instrumentation and we were discussing about the magnetic sensors or magnetoelectric sensor. So last lecture we discussed about AMR and GMR sensor the GaN magneto resistive sensors. Now today we are going to discuss about the Hall sensor which is another form of magnetic sensor as well. So the Hall sensor we can classify as a electrical sensor and as well as a magnetic sensor because the effect we measure using the Hall sensor is magnetic effect we primarily measure. So this Hall effect sensor is basically we apply a voltage across a semiconductor or a material where the electrons are flowing and we apply a magnetic field as well and based on the magnetic field these charge carriers see a force applied on that which is the Lorentz range force and based on that the output is generated. So this Hall effect sensor is very much used in measuring the rotational speed. So for example we have a rotating disk and we put a Hall effect sensor nearby to this rotating disk and we measure how much rotation per minute is going to be there on that rotating disk. So we discussed today the Hall effect sensor. So let us say we have a rotating disk and this has multiple fractions and these are nothing but the north and south poles of a magnet alternating and this disk is rotating along this axis. So we place now a Hall sensor very next to this disk.

This is Hall sensor and we can measure how much rotation this disk has. So primarily we have a Hall sensor or Hall device in this. This device is actually the sensing element and this converts periodically applied magnetic field into voltage. So we have this Hall device which is sensing element and it is converting the magnetic flux which is linked by these permanent magnet placed on this disk. This flux is converted into a voltage by this Hall device or Hall sensor. Now this developed voltage is very small in magnitude. The voltage is few millivolts only. So this very small magnitude is not suitable to process using the extra electronics. So first we have to amplify it. So most of the time when we employ a Hall device or a Hall sensor this is followed by a amplifier which is kind of a linear amplifier. We can make use of BJT or MOSFET for making this amplifier and this amplifier is used to boost this signal which is in millivolt to a range of let us say volt. So this Hall device is now followed by a linear amplifier. The output of these Hall devices goes to a linear amplifier and the purpose of this linear amplifier is amplify the Hall voltage. And for this purpose we can use a very well known common emitter amplifier configuration. So now we have a Hall device which is sensing this magnetic flux and converting it to the voltage which is in few millivolts and then followed by a linear amplifier which is amplifying this few millivolt into volt kind of range.

But the problem is when the signal comes from the Hall device that signal comes along with the noise as well which is always there in these circuits. So this noise also gets amplified by linear amplifier because the amplifier cannot differentiate between a signal and a noise. So whatever is the input to linear amplifier that is going to be amplified. So signal is also amplified but the noise also get amplified by this linear amplifier. So most of the time this linear amplifier is also followed by some filter which is can be a low pass filter or depending upon the application. So this linear amplifier is followed by a filter or sometime we use Schmitt triggers because Schmitt trigger also can be used as a filter. So this is followed by a Schmitt trigger. So we have the next stage of linear amplifier is the Schmitt trigger. And this is basically nothing but the comparator circuit. This creates basically digital pulse based on the amplified Hall voltage. So this is the complete system. Where we have a Hall device which converts flux to a small magnitude of voltage. This is followed by amplifier which converts this or boost the signal from few millivolt to volt and that we use a Schmitt trigger. Schmitt trigger is nothing but kind of a comparator. Let us say we assume that the reference value is 0.

So anything below 0 will be treated as 0 and when anything any voltage above 0 volt will be treated as 1 volt. So this Schmitt trigger converts the data or converts the input whatever is generated by linear amplifier into a digital form which is having 0 and 1 for a kind of simplicity. This signal can be easily processed by further electronics. And this Schmitt trigger also act as a filter. We will see when we discuss this Schmitt trigger today. So let us now discuss individual blocks in detail. So first is the Hall device or the Hall sensor. Hall effect sensor. So this sensor is made up of for example P type semiconductor and has 4 electrodes. So this is the Hall effect sensor. A DC voltage is applied between the left and the right electrode. So let us see how this Hall sensor look like. So we have a semiconductor material. This is our semiconductor material where we have 4 terminals. 2 are left and right. This is left and this is right. These are the terminals going out and we apply a voltage across these two terminals. So let us say this is V external for the DC supply. And other two terminals are let us say top and bottom. Let us say this side is we call top and this side we call B or bottom. So these two terminals we take out and we measure the voltage across these two terminals. This is nothing but the Hall voltage. And on top of this we have a magnet which is applying the magnetic field on this material. So we have a magnet. This magnet has north and south poles.

So this is let us say north pole, this is south pole and this has a magnetic flux linked with it. So let us say this is like this. So this is the flux which is linked now to this material as well semiconductor material. And in this material we have free moving electrons and holes. So let us say electrons are moving from right to left. So these electrons will see a force applied on them because of this magnetic field which is called Lorentz force. And these electrons will start accumulating towards the B terminal as shown here. And holes on the opposite because of the opposite charge they will see similar force but in opposite direction. So they will accumulate towards the top. So here in this setup we have a semiconductor, p-type semiconductor slab where we are applying a DC voltage and because of that application of voltage there is a current flowing in the semiconductor and this current of course is made up of electrons and holes, the charge carriers. Now when we have this magnet on top of it because of this there is a applied magnetic field on this semiconductor. When a charged particle moves in a magnetic field that experience a force that is called QvB sin theta or the Lorentz force we call it. Because of this motion of charged particle this experience a force and because the electrons are negatively charged they see this force in let us say towards B terminal and the holes which are positively charged they see the opposite the same force is the opposite direction and they accumulate towards the top. So when there is a accumulation of or the separation of these charged particles positive towards the top negative towards the bottom then because of this accumulation there is a voltage build up across this semiconductor slab between T and V the top and bottom terminal and this we measure using a voltmeter and this voltage developed is called the hall voltage. So this is how this hall sensor works.

The more the magnetic field means if the magnet is really close to the semiconductor the force magnitude is more it means the more hall voltage will be generated and this also depends on what is the velocity of these electrons and holes in the semiconductor. So here we apply this DC voltage between top between the left and right and we measure this hall voltage on the top and bottom. So because of this the free electrons move within the electric field through the hall material or the semiconductor material move within the electric field through the semiconductor material. Now when magnet comes closer to hall plate the magnetic field B creates the Lorentz force. So when magnet comes closer to the hall plate the magnetic field B creates Lorentz force. FB and the formula for this FB is minus Q V B sin theta where this Q is the normal charge on electron V is the velocity of electron and B is the magnetic field. So the magnitude of Lorentz force is minus Q V B sin theta, Q is the electronic charge which is 1.6 into 10 to power minus 19, B is the velocity of electron how fast the electron is moving into this magnetic field and B is the magnetic field the value of magnetic field how much is the magnetic field applied. Sin theta is the theta is the angle between the velocity and the magnetic field and most of the time because this magnet is very perpendicular to the motion of electrons so theta becomes 90 degree so sin theta becomes 1 so we can neglect sin theta from this equation for time being. So the Lorentz force which is applicable on these electrons as minus Q V B and depending upon whether it is electron or hole the polarity of this force will be opposite in nature.

So because of this these electrons will accumulate towards bottom and holes will accumulate towards the top we can even draw this by that arrows these holes are attracted towards the top. So this is how the volt hole voltage is being generated in these hole sensor. Now we can write the hole voltage build up in this sensor BH is equal to I into B upon ne into d and where this I is the DC current through the hole device. B is the applied magnetic field. E is the electron charge. C is the thickness of the material or the semiconductor. N is the charge carrier density. So this is the output hole voltage VH equal to IB upon nED. I is the DC current which is flowing into the semiconductor which we can measure very easily using some emitter. So all these parameters are something which we can measure very easily in a setup. B is the applied magnetic field. E is the electronic charge which is a universal constant. D is the thickness of material how thick the semiconductor material is and for precise applications precise measurement we try to keep this D very well below very very small thickness and N is the charge carrier density of the material. So this is the output voltage generated by this hole sensor. Now let us think about the sensitivity of this hole sensor.

So let us write down the sensitivity. So we have this graph for hole voltage VH. The hole voltage developed if we change the magnetic field in this direction. So when magnetic field is positive we have let us say hole voltage build up like this and in negative when the direction of magnetic field is reversed the hole voltage generated is in the reverse direction. So this is a typical generation of hole voltage versus magnetic field. So if we see the slope of this graph is nothing but the sensitivity. The slope of this graph is the sensitivity and sensitivity we can write S A equal to VH hole voltage developed per unit applied magnetic field. So this we can write I upon N E D. So this is the sensitivity of hole sensor and usually the thickness is in micrometer let us say if we can write the typical values of D which is in the order of 250 micrometer and the current in these sensors are typically of the order of 10 micro amps. So these are the typical values of D and I and sensitivity is given by I upon N E D. So how do we increase the sensitivity of a hole sensor either we increase the current I so if we increase the current which means we have to apply high voltage and get more current it means the power dissipation will be more in the holes effect that is not as wide advisable.

So I also has certain limits so beyond that those limits we cannot increase the value of I or we can reduce the thickness D so that sensitivity goes high but that also has limitations so how thin we can go in that semiconductor plate or semiconductor film that also has physical limitations we cannot go much much more thinner materials because of many other issues. So D also has certain limits so the sensitivity is dictated by the current and the thickness of the material. So this is the hole sensor which we apply a magnetic field and the hole voltage VH is developed VH is given by IB upon N E D. So this voltage now is applied or it is it goes to the next step which is the amplifier unit linear amplifier which amplify the small amount of hole voltage into a measurable volt kind of range. So let us discuss that linear voltage amplifier. These linear voltage amplifiers are nothing but the common emitter amplifiers which we which is very well known configuration. So we can draw a common emitter amplifier. So if we talk about the BJT version then common emitter amplifier looks similar to this. This is an NPN transistor. This has collector resistance and emitter resistance and on the base side we use mostly voltage divider bias. This is a simple configuration of a NPN amplifier linear amplifier. We have typically a voltage of 5 volt at the supply and this is the Rc the collector resistance. This is the voltage divider bias so Rb1 or R1 simply and R2 are the voltage divider biases. This is Re the emitter resistance and at the emitter we have a capacitor as well which is called Ce or the emitter capacitance and we use Cb and C load. This is RL the load resistance and this is typically the signal unit which is the preceding unit which is generating the small signal and applying it at the Cb and this voltage generated by this V signal. This actually gets amplified at the output node which is V0. So this is a simple structure of linear amplifier or common emitter amplifier. We will not discuss how this amplifier actually works. This can be referred to some second year basic electronics course. What the amplifier actually does this takes the signal from V sig which is applied at the capacitor at the base.

This small signal is amplified by this NPN transistor which has a gain let us say beta and the output is taken at the collector end and the collector is having a resistance Rc and at the emitter we have a emitter resistance which is needed for the stability purpose and because stability is needed only for the DC condition for AC or when we are talking about the signal it should not be there. So we connect a parallel capacitance CE which bypass this emitter resistance in case of the signal analysis and we get the boosted output at the Vout. So this is how a common emitter amplifier works. We will not go much into the detail of how it works. So this amplifier now takes the signal of millivolt range and convert it back into convert it into a volt kind of range which is now amplified to typically 1 or 2 volt or so. Now this amplified signal is applied to the Schmitt trigger. So the configuration of Schmitt trigger is very simple. We generally make it using Op-Amp where this is positive, this is negative terminal, negatively connected to ground and the positive terminal has a feedback. These are R1 and R2 and this is the output, this is 0. Now this is the configuration of a Schmitt trigger which act as a filter and it converts the data into a digital form.

So let us talk about what actually is the problem is and why do we want to employ a Schmitt trigger to rectify that problem. So the problem is when we get a data from hall device that is full of noise. The signal is not very smooth it has little kind of spikes. Then we feed this to the linear amplifier which further amplifies everything the data as well as the noise. So now the noise also get amplified. Now we need to convert this data into digital form so that we can process this data. But because of that noise it is not easy to convert that into digital form. Let us see how it is not possible and what we should do. So for example if we do not have a Schmitt trigger we just use a inverter to convert the data into digital and this is the threshold of an inverter. Let us say this is a fixed crossing or fixed threshold and our signal is something like noisy. So this is our signal which is a sinusoid but full of noise. Now if we see at this point if we have a single threshold just like an inverter, inverter works like if anything above this it will be detected as 1, anything below this it will be detected as 0. So now if we see closely here we are having 0 here but as soon as this threshold is crossed at this point we start receiving 1. But we see again this signal again goes below this threshold voltage so again it becomes 0 here and after this 0 this signal again goes up because of this noise. We see now a 1 here so we see this ideally there should be only 1 transition from 0 to 1 because the signal is this large signal and which transits from 0 to 1 only once.

But because of this noise in this section we get an additional 1 and 0. So if we convert it into digital this is like 0 then we get a small 1 which again goes back to 0 and then again 1 which continues here. So this is a undesirable thing which is like a high frequency transition or spike we can say which is undesirable and this happened because of the noise. The same thing happens actually here as well this 1 is there and then when signal goes below this threshold black line this becomes 0 again because of the noise this becomes 1 here and again becomes 0 here. So same thing we have here this goes 0 and then again for a short while it becomes 1 and continues to be 0. So these are the things which are undesirable these transitions are actually happening because of the noise in the signal. It is not signal is crossing only once this threshold but because of the small amount of noise this noise is converted into a digital data which is a high frequency noise and we do not have any means of removing it because the signal has these digital transitions. So our further electronics will treat it as a signal only. So this is the problem with noise when it get enhanced and we cannot deal with it using a single threshold which is just a black line. So instead of having this a single threshold we employ a Schmitt trigger which has 2 threshold.

It means there is a hysteresis in the graph and for going up there is a separate threshold and for going back or going low is a separate threshold and we have 2 thresholds now instead of 1 black line and these 2 thresholds will filter out this noise. So let us see the response of a Schmitt trigger. The Schmitt trigger is something like the response is this is V out and here this is V in and the response of Schmitt trigger is something like while going high this goes like this and at some point it triggers and goes to high voltage like this. So this is the threshold voltage while going high or we call it Vth threshold voltage going towards high while coming back let us draw it in a different color. So while going back when we decrease the input the threshold is different. So this is the path while going high to low and this threshold is called Vtl the threshold voltage while going low and the midpoint is that 0 voltage or the origin because we have connected this terminal to 0 volt. We can apply certain voltage here so that we can shift also this entire graph. For example if instead of 0 we apply certain voltage if Vr let us say this Vr is 0 here if Vr is not 0 then we can draw it differently. This is Vr here this Vr is 0 and this is Vtl Vth and this is Vtl. So now because of these two threshold voltage we can plot the same graph here. Now instead of this single threshold now we have two thresholds. This is Vth and this is Vtl and we plot the we apply the same signal full of noise. So now the high will be detected at this point not at this point. So even if this signal is going low here for a short while because of the noise the low will not be detected until the signal is reached Vtl. So this small amount of noise will not be detected as a signal and if we plot the output this is 0 here, this is 1 here only after this and 0 here and this 0 actually is detected till this point. So 0 will be up to here till the signal crosses Vth and here this will become 1 and then this 0 will be detected when the signal goes below Vtl so this point.

So here this is 0, this is 1 and this is 0 which is the perfect case what the signal should be and we can remove all these noises what is actually inserted by the amplifier or generated by the sensor itself. So Schmidt trigger is actually used to filter out these noises which are inherently there in the system. Now if we see carefully that the signal the output signal is little delayed compared to the earlier case that delay we can live with it, it is already is always there in the system because of we have employ the Schmidt trigger in the circuit. So this is how a Schmidt trigger works. Now let us see a small example of linear amplifiers and we can have it as a numerical problem. So one example, so a common emitter amplifier circuit. As a load resistance of 1.2 kilo ohm and a supply voltage of 12 volt. For the transistor to be switch on completely. Assume collector to emitter voltage or BCE equal to 0. And the value of emitter resistance Re if it has a voltage drop of 1 volt. Cross it. Calculate value of other circuit resistance as well. Beta for the NPN transistor is given as 100. So this is a numerical example which we can solve and the solution of this is given below. So we have this NPN transistor.

So the collector resistance or RC will come out as 1.2 kilo ohm. This is 12 volt. The value of R1 will come as 20 kilo ohm and R2 is around 3.6 kilo ohm. The emitter resistance come out to be 220 ohm. BCE we assumed 0 as given and here at this point we take the output Pout. These are the typical values of resistances what comes out after calculation. So we can do all these maps at some different time. The IC current come out like 4.58 milli ohm. So this is a small example for linear amplifiers. This is particularly covered in some semiconductor device courses like electronic devices and circuits basically is a P-TAC second year course, complete course. So we will not discuss much about how do we solve these circuits but this is typical circuit for linear amplifier. So today we discuss the Hall effect sensor and basically after the Hall effect sensor we also discuss the linear amplifier and the Schmitt trigger which is basically used as a filter for the Hall effect devices.

So, this is all for today.

Thank you.