Transducers For Instrumentation

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Lecture - 9

Thermal Sensors: Thermal RC Networks

Hello, ah welcome to the course Transducers for Instrumentation. Last lecture we were discussing about the electrical and thermal networks and we saw that the thermal networks can also be solved just like the electrical networks. For example, the resistances are replaced by the thermal resistance, the current flow is replaced by heat flow, the temperature difference is corresponding to the potential difference. So, the similar kind of laws just like the Ohm's law they are applicable to the thermal network as well. So, today we will discuss some thermal resistances and how we can connect them in series or parallel and how do we solve them. So, we discuss thermal resistances in parallel, thermal resistance which are in parallel. So, for example, we have these two materials are material A and material B with some thermal conductivity of kA and kB and we want to investigate the thermal flow when these materials are connected in parallel. So, for example, we have surface here which is surface of A and which is this is surface of B. So, the first assumption we are making is across the surface of this material A, this surface the temperature remains same. It means the temperature of the surface at this point is same across the surface.

So, this is the assumption just like a point contact in electrical networks. So, similarly we have the same assumption in thermal networks. So, this point has a temperature which is same across the surface. Similarly, for point for material B this point has the same temperature across the surface. So, this is the assumption we are making. Similarly, on the other surface the far surface we have this point where the temperature is same across the surface and we assume that there is no thermal conduction between this surface. So, there is no thermal power dissipation is not there across this. So, given these assumptions now we have temperature difference which we apply across this assembly and we want to investigate how the heat flows. So, let us say we have a temperature which is T1 or Ts1 whatever we call it. So, this is the temperature we apply at the near end and at the far end let us say the temperature is Ts2.

Now, we can write the resistance of each one of this material is for example, that R conductive for a material A is equal to L upon kA which is the conductivity multiplied by the area. So, here the L is this and the area is cross section area of this material. So, this is the R conduction for material A. Similarly, for R conduction B will be L upon kB into A the area of for example, the area of material A is A subscript A and the area of material B is A subscript B. So, these are the thermal resistances of these material A and B and because they are in connected in parallel we have the overall resistance which is 1 upon R total equal to 1 upon R A plus 1 upon R B or we can say this comes out 1 upon L upon kA into A A plus 1 upon L upon kB into A B. So, this is the total resistance which is R total of this whole assembly and this is very similar to the parallel connection of electrical resistances. Now, we can calculate the heat flow across this whole assembly when we apply this temperature difference which is TS1 on the on the near side and TS2 is on the far side. So, we can calculate the heat flow which is equal to the temperature difference which is TS1 minus TS2. This is the temperature difference just like your potential difference divided by the total resistance which is R total. So, this is the total heat flow which is equal to the difference in the temperature divided by the total thermal resistance.

This is very much equal to the electrical current which is flowing through the material that is equal to the voltage difference divided by the resistance. So, this is the parallel connection of these thermal resistances though we can more generalize it by considering that one source will be supplying this heat energy to this assembly. So, let us consider a little bit more generalized case. We have this material assembly. This is material A, this is material B with thermal conductivity KA and KB respectively and these are the points at the surface. Now, we assume that there is a source of heat energy which is here at the temperature T1. This is supplying some heat which is going to both of the materials one here from this point to this point and one from here. This mode of the heat transport is convection because there is no direct contact between this point and this point. Similarly, on the far side we have a receiving end which is at temperature T2 and this heat is flowing from this point to the far end. This is also the convection mode and inside the material the mode of heat transport is conduction. Now, we can write the resistance similarly to the previous slide where we have 1 over R total equal to 1 upon RA plus 1 upon RB the resistance of the path A and the resistance of path B. Now, the path A has 3 subsections. One is this path where the heat is flowing from T1 to material A through the convection mode and this is the second section where the mode of transport is conduction and heat is flowing from this point to this point and the third section is where the heat is again flowing through convection from the material A to the point T2. So, we can write the overall resistance of the upper path like RA the thermal resistance through path A is equal to 1 upon H1 into AA. Here the H this H is the coefficient for convection.

So, 1 upon H1 into AA which is the area of this surface AA plus the second section which is conduction which we can write L upon KA into AA very similar to the last slide and then again the third section which is again convection and we can write 1 upon H2 into AA. So, this is the overall thermal resistance through the path A and similarly we can write for the path B which is again 3 section this is first section this is second section and this is third section and we can write for RB is equal to 1 upon H1 AB plus for the second section which is conduction that is L upon KB into area of B plus the third section which is again convection 1 upon H2 into area of B. So, these are the respective values of RA and RB and we can calculate the total resistance 1 upon R total is equal to 1 upon H1 AA plus L upon KA into AA plus 1 upon H2 into area of A plus 1 upon 1 upon H1 into area of B plus L upon KB into area of B plus 1 upon H2 into area of B. So, this is how we can write the total resistance of material of two materials when they are in connected in parallel and we can also write this equivalent model of this whole assembly that we can write something like this. We have the first point which is T1 here similar to this we have T1 and then we have the first resistance which is in the form of convection and the value of this is 1 upon H1 into AA. The second element in this is because of the conduction mode and that is L upon KA into area of A and the third element which is again because of the convection to this temperature T2. The value of this is 1 upon H2 into area of A. So, this is the model for the upper path the lower path is also similar to this. The value of this we can write similarly 1 upon H1 into area of B this is L upon KB into area of B and this is 1 upon H2 into area of A. So, this network is very similar to the electrical network and we can apply any temperature difference T1 and T2 and calculate how much the heat will flow from the point T1 to the point T2.

We can apply all kind of Ohm's law to calculate all this heat flow from T1 to T2. So, we can write the heat flow for this assembly which is again similar to the last slide which is T1 minus T2 divided by R total. R total is the whole combination of this model. So, this is the thermal resistance connection in parallel. Now, we consider little complicated case where we have multiple materials joined together in terms of series and parallel and see how we can calculate the heat flow in that whole assembly. So, we calculate thermal resistance of series parallel network. So, for example, we have assembly where we have different materials. This is material for example A. Then we have material B and we have material C and another material is connected like this which is material D. And correspondingly we have the thermal conductivity of these materials which is Ka, Kb, Kc and Kd. And the length of these material is for example LA and LB. LB is equal to LC and this is LD. So, this is the whole assembly of materials and we want to calculate how much heat will be flowing through this assembly if we apply a certain temperature difference across this assembly. So, let us say we apply a temperature difference which is T1 this side and this side is T2. Whole area of this is A. So, now we need to make an assumption here. Similarly in the first slide we had assumption that at the point of contact the temperature is same across the surface. So, similar assumption we need to make here that there is no temperature difference perpendicular to the x axis. For example, the heat is flowing in the x direction. The heat flow is this side and there is no heat flow perpendicular to this.

Means the surfaces which are normal to x direction they are isothermal. The heat will not be flowing from material B to material C. The heat will be flowing only from material A to material B and material A to material C and then back from material B to material D and material C to material D. So, this is the assumption we need to make. This is the assumption that surfaces which are normal to x direction are isothermal. So, they are at the same temperature of each other and there is no heat flow in the perpendicular to x direction only the heat is flowing from T1 to T2 in x direction only. So, now we have we can treat them like a pore resistance where we have this material A which has certain resistance. Then we have two resistances corresponded to material B and material C and then back to material D. And the value of these resistances we can calculate just like for the conduction case which is L upon L A upon K A into area of A and this is for material B which is L B divided by K B into area of B which is actually half of the area of A but we can write for generality area of B this is material D and we can write L B L C divided by K A K C into area of C and this is material D we can write L of D divided by K D into area of D and the temperature applied is T1 this side and T2 this side. So, we can solve for this series parallel connection which is R A plus R B parallel R C in series with R D that will be the total resistance and the heat flow we can calculate T1 minus T2 divided by the total resistance.

The heat flow for this network will be T1 minus T2 divided by the R total and R total we can calculate of this thermal resistance this is R total. So, this is how we can solve a thermal network very similar to the electrical networks. We need to discuss one more point of the thermal resistance which is equal to the contact resistance of electrical network. So, similarly in thermal networks we have thermal contact resistance very similar to the electrical contact resistance. So, this is the thermal contact resistance. So, when we have two materials that is a material A and we join this with material B this is material A this is material B and there is a heat flow from the left to the right. Now when these two materials are joined together they behave differently at the surface is where they are having a contact with each other that is called the contact resistance which is different than their internal their intrinsic resistances. So, the reason for this is for example, we have this surface which is in contact of the surface of material A is in contact with surface of material B. When we join them together we assume that the whole surface is in contact with each other, but in practicality this is not the perfect contact. If we zoom in at this point if we zoom at this point very closely and we see the surface is there is actually not in very much contact. If we assume that this should be the point of contact or the physical contact actually the material A let us take the material A with blue color the material A surface is something like this because of the surface roughness material A is like this and the material B the surface is like this. So, we see that there is no proper contact between material A and material B because of the surface roughness they are not very much in close contact. So, now if the heat is flowing from material A to material B that heat will have two paths one is the path where they are in contact here material A is in contact with material B. So, heat will have different resistance which is let us say R1 this resistance will be different than this resistance where these materials are not in contact this blue curve is very far away than the green curve and we have the different resistance R2 and we can calculate whole of the resistances of this which are different different values because of the surface roughness and this gives rise to the contact resistance or the thermal contact resistance. Thermal resistance arise due to surface roughness and this is again just like a electrical contact resistance this thermal contact resistance is also a problem in proper heat conduction and that is why if we want to have a good heat conduction from material A to material B generally we try to put some kind of epoxy on the surface of this.

So, that the amount of surface which is in contact with each other that increases and this contact resistance actually goes down. So, we sometime put some epoxy on the thermal conductive epoxy to reduce this contact resistance. So, this thermal contact resistance is very similar to the electrical contact resistance where we apply some 4 point Kelvin probe method to get rid of the contact resistance similarly, we have thermal contact resistance in thermal networks. So, next we discuss the thermal RC networks we will this consider some practical cases where we have multiple assemblies and we try to investigate how much the heat will be flowing from the source to the ambient temperature and we will we will consider some real applications where we can apply these thermal networks and solve for the thermal power dissipation. So, we consider the case of a IC package where we have a semiconductor IC which is silicon based IC and we have some epoxy connected to it and then some heat sink connected to it the transistor on the silicon chip will be generating some heat and how that heat will be transferred to the ambient temperature. So, let us say we have a semiconductor which is silicon and on this we have P plus device made of P plus material P plus doping on the silicon below the silicon we have some dye attach and below this we have some heat sink. So, we have now 4 different materials here the first material is the P plus or P plus well we can assume it is like a resistance which is generating heat when we apply a voltage across it and this P well has certain thermal resistance which is Rth let us say this is 1 and certain capacitance the thermal capacitance let us say Cth1. Similarly, we have another material which is silicon and Rth2 is the thermal resistance of silicon and Cth2 is the thermal capacitance of silicon. The third material here is this dye attach and thermal resistance is let us say Rth3 and Cth3 is the thermal capacitance and after this we have the lead frame or after that we will have heat sink. So, now we have this whole assembly which is practical assembly in any electronic circuit.

Now, we need to make a model of this whole assembly so that we can solve it for power dissipation. So, we can make a model some similar to this is the delta T which is the temperature difference being generated by this by this P plus this is T junction then we have a thermal capacitance connected to it which is Cth1 and Rth1 then this is connected to silicon which is Cth2 and Rth2. Then again the dye attach is connected to it which is Cth3 and Rth3. So, this is the whole assembly till this dye attach and further a heat sink is connected to this let us take the different color here this heat sink is connected which is dissipating this heat to outside environment which can be modeled just like a thermal capacitor and the thermal resistance which is in low in magnitude.

So, this is heat sink. Now, when the junction that or the device inside this chip they are generating heat that heat need to be flow outside to the environment because the junction temperature has its limits the junction temperature should not exceed a certain value. So, that the device can perform its operation satisfactorily. So, we need to have this whole network efficient enough so that the heat generated inside or this delta T the heat can be transferred from this junction to the outside environment. Now, typically in data sheets a value of Rth is given for DC case this the value of Cth the thermal capacitance is not given generally because we assume that in steady state condition or where the heat has is flowing in steady state condition there is no transient there this capacitance can be omitted. So, this thermal capacitance is exactly like our electrical capacitance where in the case of DC currents the capacitance can be removed similarly for the steady state condition of heat flow these thermal capacitances can also be omitted and we can easily calculate how much current will be flowing just based on the thermal resistance which is here in series Rth1 plus Rth2 plus Rth3. So, in data sheets typically Cth value is not included. Because, in case of steady state this can be omitted. So, the steady state condition for thermal RC network is very easy to solve we just need to remove all the thermal capacitances and just the thermal resistances will be added in series or parallel whatever is the case and we can calculate how much heat will be flowing based on that we can calculate we can calculate how much junction temperature will rise and this rise need to be within the limits of semiconductor devices specified by the data sheet. So, next so this is the thermal RC network for DC conditions or steady state conditions. Let us calculate one example a switch has its resistance which is rds on to 24 milli ohm this is the electrical resistance and the current flowing through this switch is 5 amp i is 5 amp.

So, this is electrical switch 24 milli ohm and the current is 5 amp. The maximum thermal resistance Rth maximum Rth is equal to 55 degree centigrade per watt ambient temperature which is T ambient or Ta is 85 degree centigrade we need to find the junction temperature. So now first we can see this we have a electrical resistance which is dissipating some power then we need to calculate how much power it is burning that power will be in terms of heat and that heat will be flowing from this resistor to the ambient temperature to the ambient and the thermal resistance of this resistance is 55 degree centigrade per watt and ambient temperature is given 25 how much junction will temperature will rise. So, first we calculate how much power is being generated. So, the power dissipation is equal to I square R 5 square multiplied by 24 milli ohm this comes out to be 0.6 watt. So, this 0.6 watt of power is being generated by this electrical resistance and this power because this is burned inside this resistance this is in terms of heat this heat is going to flow outside depending upon the junction temperature difference and the ambient temperature. So the thermal resistance is given is as 55 degree centigrade per watt means for a heat flow of 1 watt junction temperature will rise 55 degree centigrade. So, the total junction temperature will be equal to the ambient temperature plus the temperature rise because of the heat flow. So, we can write T A which is the ambient temperature plus the thermal resistance which is 55 degree centigrade per watt into the power dissipated which is 0.6 watt. So, this temperature is at T 5 plus at T 3 it comes out to be 118 degree centigrade. So, this is T junction means the junction temperature will rise to a steady state value of 118 degree centigrade when the ambient temperature is 85 degree based on and this temperature rise is due to the electrical power dissipation which is being happening inside the resistance. So, this is the simple case of DC condition where we are assuming that there is no transient response and the heat is flowing continuously from the resistance to the ambient temperature. Next we consider a more generalized case of transient response where the heat is actually being generated through pulses it is not a steady state condition where the source is at a particular temperature and the heat is flowing steady state.

Now the source which is a electrical device that is being turned on and off and that will generate some transient response in the heat flow. So, that we consider in transient response. So, if we try to solve the same model which we just saw here this is the model of this thermal network which is very similar to electrical network and we try to solve with this series and parallel connection of resistance and capacitance we will get expression very similar to what we have in electrical networks and that total impedance now we call it Zin in terms of omega which is the angular frequency. So, the model will look something like this which is 1 upon 1 1 upon j omega C Thevenin plus 1 upon R thermal 1 plus 1 upon j omega C thermal 2 is C thermal 1 plus 1 upon R thermal 2 and plus this will continue till the last element it depends on how many number of elements we have we will get this kind of expression. Now looking at this expression we can say that this model is fairly complex and this is difficult to solve we have in practical cases we have multiple thermal resistances and thermal capacitances. So, the number of terms in this expression will be very high. So, we do not want to solve this kind of model for our practical network.

So, what we have in real practice is a thermal graph and this thermal graph is generated by industries based on that they do extensive characterization of their assemblies and they come up with this thermal graph using this thermal graph we can apply a pulse and calculate how much the thermal resistance will be there for that particular assembly and this thermal resistance is particular to that thermal assembly it is not usable by any other assembly. So, this thermal graph looks something like this. So, this is a thermal graph which is generated by the industries by extensive characterization. So, what this thermal graph says on the y axis we have this junction thermal resistance and on the x axis we have the t pulse which is the time period of the pulse. Now in the case of periodic event when we have pulse applied to the network let us say this pulse rises at this point and fall at this point. So, this time between rising and falling this is the time period time which is t pulse compared to the total time period which is t and the duty cycle of this pulse is given by d which is equal to t pulse upon t. So, in this particular case we have duty cycle of 50 percent because half of the time the pulse is on and half of the time the pulse is off. So, this thermal graph has multiple tracks on this. This for example, this is the case for single pulse where we just apply one pulse it turns on and turns off and it remains there there is no extra pulses. So, in the case of single pulse we take this graph if the duty cycle of our pulse which is applied here is 1 percent then we take this graph 1 percent if we have 10 percent we take this graph and if the duty cycle is 50 percent we take this graph.

So, this is how we take this thermal graph and we calculate how much the thermal resistance of our assembly will be. So, using this graph we can calculate our thermal resistance instead of solving this complex model. So, instead of this complex model we go for thermal graph. Let us take one example of transient temperature. In this example we have a certain assembly and we apply a single pulse of 400 watt to this semiconductor package for 200 microseconds. So, let me draw this pulse. So, we have a pulse which is this pulse is 400 watt in magnitude and the pulse is 200 microsecond. This is time this is 200 microsecond and this is power. So, this is the pulse which we apply to a certain assembly for which we are given the thermal graph and we need to calculate how much junction temperature will rise for that particular assembly. And the ambient temperature generally it is 25 degree centigrade or the T ambient is 25 degree centigrade. Now we need to calculate the junction temperature. So, how to solve this? We are given that the power dissipation is 400 watt because the pulse the power of this pulse is 400 watt. The thermal resistance now we need to calculate that for this assembly how much will be the thermal resistance. Remember if we actually solve the package for this thermal resistance we may have multiple thermal resistances. For example, the silicon will have its own thermal resistance ceramic package dyes bonds every element has will have its own thermal resistance. So, instead of using that we go for a thermal graph and in thermal graph we need to know what is the duty cycle.

So, here it is a single pulse it is a single pulse we need to calculate the thermal resistance of this for 200 microsecond. So, let us go to the thermal this is the thermal graph and for single pulse we need to take this graph which is for this single case and we can see for 200 microsecond here it is around 200 microsecond the value will be around 0.083 degree centigrade per watt. So, this we can calculate 0.083 through this thermal graph and we take this back to our calculation. The thermal resistance is equal to 0.083 degree centigrade per watt. Now the total junction temperature will be equal to T ambient plus the temperature rise which is the power dissipated into the thermal resistance which is equal to 25 degree plus 400 into 0.083 this comes out to be 58 degree centigrade. So, the junction temperature Tj will be 85 degree centigrade and if we plot this rise in the temperature it will look something like this we have this time axis and this is the junction temperature which will rise when there is a power dissipated. This will be originally at 25 degree centigrade this is 25 and this will rise to its peak value and then again fell down and this peak value will be 58 degree centigrade.

So, this is how we can calculate the junction temperature of the whole assembly. So, this example is in case of single pulse where we have applied just only one rising and one falling edge. Let us take one more example where instead of one single pulse we apply the train of pulses to this assembly and calculate how much the temperature will rise. For comparison we will take the time period as same as 200 microsecond, but now we will take the power which is very less compared to the last slide. Now we take 1.44 watt only as the peak power. So, this is the pd, this is time and we apply. We apply these pulses which is in 1.44 watt of magnitude and the time is t pulse is 200 microsecond and duty cycle is 50 percent. The ambient temperature is same as 25 degree centigrade. Now we want to calculate how much junction temperature will rise if we apply this train of pulses. So, the power dissipation is same as given to us. The power dissipation is given to us as 1.44 watt. We need to calculate the thermal resistance. So, this thermal resistance we need to calculate through the thermal graph. Our duty cycle is 50 percent and the time t pulse is still same as 200 microsecond. So, we go back to that thermal graph. Here for the duty cycle of 50 percent we need to take this graph which is shown here. This is for 50 percent duty cycle and for the same 200 microsecond, this is approximately 200 microsecond. The junction temperature, the thermal resistance Zth comes out to be 23 degree centigrade per watt. This is approximately 23. So, this reading we can take from thermal graph and put it back here which is 23.

Now we can calculate the junction temperature is equal to ambient temperature plus the temperature rise which is Pd into Zth thermal resistance. This is 25 degree plus 1.44 watt into 23 degree centigrade per watt. This comes out to be 58 degree centigrade. This is the junction temperature. So, this is the case in terms of periodic pulses where we have this periodic pulse applied to the assembly and this is the temperature rise. If we plot this junction temperature with respect to time, the graph will look something like this. We have initial temperature which is 25 degree and the temperature will rise when the pulse is applied. Then it will go back, then again it will rise, then it will go back, then it will go rise, then it will go back. So, it will achieve a peak temperature which is given by 58 degree centigrade. So, in steady state condition when we keep on applying these pulses, the temperature will rise to 58 degree centigrade. One thing to note here is in the last slide we applied 400 watt of power, but the pulse was a single pulse. So, the temperature rise was also 58 degree, but if we apply a train of pulses even if the magnitude is very less which is 1.44 watt compared to the 400 watt earlier, the temperature rise is still same because these periodic pulses will keep on raising the temperature of the assembly and causes a more rise in the temperature which is not beneficial for semiconductor devices. So, this is how we solve all these thermal networks. It is very similar to the electrical networks.

So, this is all for today.

Thank you.