Design of Mechanical Transmission Systems

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Week – 10

Lecture – 27

Lecture 27_Brake: Single Stop Braking and Repeated Braking – Temperature Analysis

So, good morning to all. So, we will continue above the thermal analysis of a brake system. So far we have discussed various aspects. In fact, we have understood about the brake energy and braking power and also in last lectures we have done about the how the brake power is absorbed individually with respect to lining aspect and also with respect to drum and disk aspect. In fact, the power absorption we have discussed for all three types, when we talk about all three types about single stop braking, repeated braking as well as the continued braking. So, now, today's lecture we will understand what will be the temperature. I am talking about the temperature analysis during the single stop braking and also repeated braking and finally, we do with the continued braking also. So, all three things we are going to learn from today's lectures. Just wanted to understand about the single stop braking. The purpose is I need to understand how much temperature right is going to be taken place between the rotor and the drum that is the main motto. And I am sure you would know that in single stop braking the purpose is you are allowing the vehicle to maximum speed and apply the brake right that is what happened.

And the since the time is the braking time too small there there would not be any convective heat transfer, there would not be any you know heat dissipation from the things only the heat transfer will take between the the brake lining and the drum that is what is happening right nothing else. So, no convective heat transfer single stop and all braking energy is absorbed between the brake and lining. So, in that case how can we find out the temperature aspect. So, the heat penetration before understanding about the power we need to understand the heat penetration, no convective heat transfer single stop braking. All brake energy right is absorbed by the brake lining and disc or drum or rotor or you can say rotor also all are same, disc and rotor are one aspect, drum is other aspect they are same. So, heat penetration time to reach the outer drum radius.

Heat penetration time you can say (t_p) right to reach the outer drum radius. So, this is the outer radius surface outer drum surface or disc surface is usually it depends upon the length it depends upon the length and what else material properties right exactly excellent. So, it is depends upon the length and material properties.

$$t_p = \frac{L^2}{5 \propto}$$

L is half-thickness of drum or disc

α is thermal diffusivity

$$\alpha = \frac{k}{\rho C}$$

k is thermal conductivity of rotor/drum

ρ is density of rotor/drum

C is specific heat capacity of rotor/drum

So, this is what happen. So, the penetration it depends upon the thing. So, L we know that L is what is the L it is a half thickness of the drum or disc. It is half it is not full L is the half thickness of drum or rotor yeah that is fine. So, we need to understand since we talking about the symmetry aspect.

So, we want to know how the heat transfer taken from the outer surface to the mid surface remember, this is your what you call it disc or rotor you can say that, this is your pad right both sides are there. So, when these two rub heat generated happens right, the heat generation reach to the until mid of the rotor or drum that is why we have to find out. So, for a disc or drum right the time until the heat flux as we as reached. So, since we are talking about the thermal aspect this is (Q) is the heat flux, but already you know that the heat flux nothing, but your brake power right, that is a brake power as reach to the the midpoint in solid disc or drum. Then that

$$T_{max} - T_i = \left(\frac{5}{18}\right)^{\frac{1}{2}} \times \frac{Q(t_b)^{\frac{1}{2}}}{(\rho C k)^{\frac{1}{2}}}$$

where t_b = Brake time.

For symmetry the penetration time $t_p = \frac{t_b}{2}$

normally since we are talking about for symmetry right the penetration time right usually the penetration time t_p equal to the half of the brake time obviously. So, how the heat is transferred until the vehicle stop right until the moment you apply the brake that is where the energy converted, your kinetic energy is converted into brake energy. So, from the moment you apply the brake till reach to zero velocity right. So, that is the thing. So, that is your braking time within the braking time half of that would be the the penetration time to the heat penetrate at the midpoint of the disc or drum aspect.

So, this is the equation for a single stop braking aspect. Now, we will move for the repeated braking aspect. So, what is the understand repeated braking right. So, yeah before going to repeated braking I would like to emphasize since we are talking about the properties of the drum or disc right, we are talking about density, specific heat, thermal conductivity k and the diffusivity α. So, this is the ρ ok and C k and α all the values for the respective brake lining expect to pad right and the respective drum and disc is given.

In fact, these are the value I have taken from Brake Design by Rudolf Limpert ok that is the book where I have taken this reference. These are standard recommended values, these are the values we are going to use them for our calculations ok. So, these are the standard thing of course, there are slight variation if you use different material, but generally this can be taken for our analysis yeah this is the brake design values. Now, we will move on to the temperature analysis repeated braking. So, in repeated braking a similar to single stop ok. In single stop you are allowing accelerating the vehicle to the maximum speed and apply a brake right to bring down to the 0 velocity, a complete stop.

Whereas, this is not the case ok this is what you do, you are accelerate for a certain speed then apply a brake to bring down to certain speed or you can be 0 also again accelerate to the maximum one particular speed bring down to the lowest speed like that you keep repeating. So, by doing that you are allowing the system to cooling also right you are allowing the system cooling whereas, in single stop there is no possible for cooling. So, since the cooling is taken place obviously, you would expect conduction, convection apart from conduction you will have a convection also right, that is what I have discussed in the previous lectures for repeated braking remember h right the convection of the rotor. Conduction of the pad those things we have discussed in fact, we found out the heat transfer individually for the pad and the lining also ok. So, the as I said a vehicle is decelerated at a given deceleration from test speed to lower or 0 speed after which the vehicle again accelerated to the test speed and the braking cycle is carried out repeatedly this is called a repeated braking.

So, in analysis what we are going to do we are assume a certain things disc drum is a lumped system heat transfer coefficient and thermal properties are constant otherwise it will be too complex and the temperature is uniform throughout the disc and drum and it is function of time ok.. what do you understand lumped mass what do you mean by lumped mass? Yes, how do you understand lumped mass you take the some kind of sand ok if you hold it you know it will form as a solid the moment, you crush it should become crumble right that is called a lumped mass you do not take it as a otherwise the analysis is difficult to achieve. So, assuming this as a lumped mass and sorting out ok. So, by doing that so you first apply a acceleration to the particular speed brake down right. So, there is a deceleration again accelerated a decelerated. So, this is happening with the cooling.

So, whenever you do for one cycle to second cycle, second cycle to third cycle there is always ΔT will be increasing certain temperature rise will increase right. So, we need to understand what would be the temperature rise right of the rotor or drum yeah ok. So, in fact, as I said remember. So, this is a repeated braking. So, heat transfer is taking place you can see that, this is the where the rubbing is happening right.

So, you have a convection of your disc you can see that and there is a conduction takes in place again this is the where again conduction happening, one conduction, there is one more conduction between your the brake lining as well as the pad also right that is also there. I think those are things we have discussed in the previous lecture. In fact, I would have drawn this similar to this diagram remember right yeah this is what I would have drawn also in the last lectures you can see that. So, this is a half of your rotor right and you can see this is the convective heat transfer aspect then, this is the your conduction thing and again one more conduction happening between your the pad and the lining things yeah. Just wanted to make sure that you understand for repeated cycle assuming that this is I am drawing with the time with respect to time this is a t ok you say that this is a acceleration or deceleration it does not matter either way it is fine ok.

So, initially what happen you will make sure that you will reach certain height right then you apply the deceleration to bring down to certain speed again, accelerate, decelerate right and accelerate at this so on this is what happening this is what happening. So, if you look at this is the time right. So, the actual braking time happening when you reach the maximum speed to the deceleration thing this is your braking time this is your braking time t_b. So, what is this time what you call this time may be I will say that. So, this is has been done, now I am increasing this my acceleration rate to speed.

So, what you call this timing? It is a cooling time, there is no brake right, we are not applying it is a cooling time you are allowing the brake to cooling time. So, this is your t_c. So, this is the total braking total time this is the total one cycle time. So, within that you have a braking time and cooling time both are there and if you are interested you can look at normally your cooling time is much greater than your braking time normally cooling time is much greater than things. So, we want to understand within the braking how much temperature is going to be rise in the brake system.

The increase in temperature of rotor or drum ΔT I need to understand. So, ΔT is again the amount of heat absorbed in the rotor

$$\Delta T = \frac{Q_R t_b}{\rho_R C_R k_R}$$

Q_R right, then your braking time then what else you expect your thermal diffusivity right ρ c k. So, this is the Δ incremental temperature increasing I am sure you know Q_R equal to brake power absorbed by the rotor and you know that right these things are understood. So, the ρ is density C is a specific heat capacity right then k is thermal conductivity and suffix R indicate about the ρ rotor right suffix R indicate about the rotor right. So, as I said we are now I know what is the temperature for one single cycle when you apply a brake right from acceleration to these things.

Now, I need to understand about the lumped formulation results in a differential equation for cooling of the brake after the n^{th} break application. So, I am straight away going for the equation rather than the giving you ok. So, I need to have a two equation, what is that temperature before applying a brake that is one equation and what is the temperature after applying a brake that is what I need to understand right. So, for the n^{th} brake assuming that temperature before again n^{th} brake application right

$$\left[T_{(t)} - T_{\infty}\right]_b = \frac{\left[1 - e^{\frac{(-(n_a - 1)\times h_R \times A_R \times t_c)}{\rho_R C_R V_R}}\right] \times \left[e^{\frac{(-h_R A_R t_c)}{(\rho_R C_R V_R)}}\right] \times \Delta T}{1 - e^{\frac{(h_R A_R t_c)}{(\rho_R C_R V_R)}}} \quad (1)$$

Where n_a is number of brake applications

h_R is the heat transfer coefficient

A_R surface area of the rotor

V_R means swept volume of the rotor

Any other term are we missing here? We know h_R we know A_R t_c is the cooling time ρ C all are known to you just a new term we have volume yes I think volume we have and h is already discussed things. So, this is equation you can say that number 1. This is before nth brake now we need to understand the relative temperature after the yeah just one more information T_∞ is here your ambient temperature or room temperature ok this is a ambient or room temperature.

Shall I move on to yeah. So, the relative temperature after n^{th} brake application.

$$\left[T_{(t)} - T_{\infty}\right]_b = \frac{\left[1 - e^{\frac{(-n_a h_R A_R t_c)}{(\rho_R C_R V_R)}}\right] \times \Delta T}{1 - e^{\frac{(-h_R A_R t_c)}{(\rho_R C_R V_R)}}} \quad (2)$$

So, this is the you can have equation number 2. So, you have to find out relative temperature of before n^{th} application and relative temperature of after n^{th} application. So, this is the way you need to find the relative temperature in repeated braking system ok.

Now, I will the last one I will move for the temperature analysis for continued or drag application. This is simple equation continues braking when the brakes are applied during the downhill right. So, cooling must be always considered right yeah. So, what do you understand ok. So, I am sure you know single stop breaking, repeated braking is fine.

In continuity braking what is the purpose of continuity braking you are in the downhill right the vehicle is downhill you need to move down right you need to move down. So, the purpose of braking what is that you want to stop the vehicle or you want to control the vehicle you have to control the vehicle. That means, you have to maintain certain speed touch away that the vehicle is keep moving right touch away that you have to apply the brake understand right. So, here the purpose is not about the stopping, but controlling. So, that should not have any catastrophe failure that is the way the.

So, when you do that. So, will you apply deceleration suddenly very high, no right you know, you will apply a small amount of brake and allow the continue things. That means, it is kind of repeated breaking, but ok, but not exactly, but completely different from the single stop ok. So, obviously, there will be a cooling system also right. So, in the case the temperature response. So, if you want to understand the complete how to get this temperature aspect with the heat transfer I can reference some books you can go and study right. Drum and disc right during it is called the drag braking what do you understand drag, what do you mean, another literal meaning of dragging what do you understand yeah drag. Drag means keep stretch right keep allow the system, but in control manner that is called drag. So, when you do that usually you will have one initial temperature right you will have one initial temperature apart from the ambient temperature as you applying.

So, the heat is generated, but again certain amount is dissipated during the cooling time also. So, we need to understand what is the exact temperature you would experience during the drag aspect

$$T_{(t)} = \left[T_i - T_\infty - \frac{Q_R}{h_R A_R}\right] \times e^{\frac{(-h_R A_R t_c)}{(\rho_R C_R V_R)}} + T_\infty + \frac{Q_R}{h_R A_R}$$

Where T_i = Initial temperature

T_∞ = Ambient temperature

$T_{(t)}$ = Final temperature

T of T small t T i T infinite Q r is a heat absorption by H r A r remember you have a cooling also. So, there is a convective heat transfer into E minus H r A r into T i tau r C r V r. So, this one thing then again you will need to have your ambient temperature plus Q r H r and A r so this is the thing. So, where T i is the initial temperature, T infinite is the ambient temperature and T (t) is the final temperature irrespective of the repeated braking or continued braking.

I think these are the thing you need to understand for the thermal analysis. Of course, still one more topic we have to see where is the design limit, what is the design, whether what are the material we have chosen right, whatever the vehicle weight, the power and the size is sufficient for the given the brake that those things we are going to discuss in later class. Let us do some couple of small problems so that understand about this braking aspect. Problem number nine, we did problem number eight for the selection of the brake lining remember based on the SAE code. Now, we have problem a Federal Motor Vehicle Safety Standard 105 required burnishing of the vehicle of the brake at gross vehicle weight GVW from a speed of 64 kmph at a deceleration of 3.66 m/s^2 for 200 stops. This is for 200 stops. The cycle descent is 1.61 km and the approximate cooling time is clearly given 88 seconds. Compute the average break temperature after 5^{th}, 10^{th} 200^{th} stop. Use the data that follow. So, the vehicle is moving on a plain road with the deceleration rate is clearly given. So, you need to identify the temperature for 5^{th}, 10^{th} and 200^{th} stop. Use the following information 15 percent of total brake power is absorbed by the one rear brake. The brake drum volume is clearly given, what is the volume, the brake cooling area A_R is given 0.051 m^2. Then convective heat transfer coefficient also given and the vehicle weight is given. What is this problem? This is repeated braking or drag braking? It is a repeated braking. So, the data clearly given you have the vehicle weight is 16.458 kN that is clearly given. So, then the deceleration rate also clearly given and the distance also given 1.61 km and the cycling total the approximate cooling cycle time is given 88 cycle that is also given. Then h also given. V_R A_R all those given. What are the other information missing? Your density ρ_R right and your specific heat capacity C_R and thermal continuity k_R those values are missing. So, those value you should take it from this table.

So, you choose your density value 7228 please write down the values, these are the value you need to know. So, you need to have a density C specific heat capacity and k thermal continuity and thermal diversity depends on the equation we are going to use all those values. So, how are you going to solve this problem? First of all we have to understand how much heat is absorbed by the rotor right that is the first step. How much heat is absorbed by the first by the rotor that is the first step we need to understand. The P average or else Q_R the heat absorbed by thing of the rotor.

$$P = Q_R = \frac{K_m W V_1 a}{2g} = \frac{1 \times 16458 \times 17.78 \times 3.66}{2 \times 9.81} \times 0.15 = 8.188\ kW$$

W = 16.458 kN

K_m = 1

$V_1 = \frac{64\times10^3}{3600} = 17.78\ m/s$

a = 3.66 m/s^2

This much energy is developed this much energy is developed how much energy is absorbed by the rotor 15 percent that is what is given. So, 15 percent means into 0.15 right because that is the energy only we want right not the entire break energy that to the rear aspect okay. So, can you tell me how much energy you are getting Q_R. I think you must getting 8.188 so much kW this much energy should be absorbed by the your rotor okay yeah that is one thing is there. So, what is the breaking time t_b.

$$t_b = \frac{V_1}{a} = \frac{17.78}{3.66} = 4.9\ s$$

but the total cycle time. So, even though it is a cooling time is given the total cycle time including cooling time how much is it 88 second is given remember when we discuss about ΔT we always ignored, because your cooling time is much higher than the your braking time now you can see that how much 4.9 second is your braking time out of 88 seconds. So, we have enormous time for the cooling aspect okay. So, now that is done now the second aspect we need to find out what would be the Δ incremental that is constant all the time right ΔT is always constant.

I had to find temperature rise. So, what is the ΔT we got already remember.

$$\Delta T = \frac{Q_R t_b}{\rho_R C_R V_R} = \frac{8.188\times10^3\times4.9}{7228\times419\times0.00057} = 23\ K$$

Where ρ_R = 7228 kg/m^3

C_R = 419 J/kg/K

V_R = 0.00057 m^3

So, initially we found out what is the brake absorbed by the rotor that is one step we have done, the second step we are able to find out the ΔT for each cycle is going to be now we have to find out the temperature rise after fifth tenth and two hundred cycles that is what we are going to do that. So, that means we have to choose equation

$$\left[T_{(t)} - T_\infty\right]_b = \frac{\left[1 - e^{\frac{(-n_a h_R A_R t_c)}{(\rho_R C_R V_R)}}\right]\times\Delta T}{1 - e^{\frac{(-h_R A_R t_c)}{(\rho_R C_R V_R)}}}$$

n_a = 5, 10, 200

T_∞ = 299 K

So, this is the equation we have to utilize okay for calculation yeah. So, the n_a we have to use it first problem for five cycles then n_a equal to ten then n_a equal to two hundred right, for each fifth cycle tenth cycle and two hundred cycle we need to find out what will be the final temperature okay. So, we can assume your infinite ambient temperature equal to two hundred ninety nine Kelvin let take this is the value right you assume it your temperature the ambient temperature yeah.

So, this is the temperature that we have to use. So, what I am going to do I will straight away come with the answers rather than substituting. I have shown the method how to do it you do it at home. So, I am going to straight away give the answer for fifth cycle right for fifth cycle will say this

$$For\ 5^{th} cycle : T_5 - T_\infty = 72.9\ K$$

$$For\ 5^{th} cycle : T_5 = 378K$$

$$For\ 10^{th} cycle : T_{10} = 392\ K$$

$$For\ 200^{th} cycle : T_{200} = 399\ K$$

So, what is your observation? So, at the fifth cycle the temperature three hundred seventy eight at tenth cycle temperature is three hundred ninety two Kelvin and two hundred cycle the temperature is three hundred ninety nine Kelvin. So, what is your observation? Remember the gap between a tenth cycle and two hundred cycles, the tenth cycle the temperature shown three hundred ninety two Kelvin whereas, two hundred cycles shown three hundred ninety nine Kelvin.

So, what is that gap only seven Kelvin is difference in other words the maximum temperature observed by the brake right the maximum temperatures is how to it is not observed it is achieved within the few cycles am I right for T_5 already I have reached three hundred seventy eight okay, tenth cycle three hundred ninety two Kelvin only shy of seven Kelvin right for two hundred cycles. So, even though you do how do I say that you do repeatedly right the maximum already achieved within the few cycles then you will ask question then why it is not increasing, obviously you are allowing the cooling time. So, this is understand now the cooling time it is takes place to maintain that whatever the maximum temperature attained in the brake okay right you may ask question why we are doing we are talking about single stop braking then you are talking about the repeated braking then talking about drag stop braking why we are doing in three different aspects what is the reason just think about that those aspects I will discuss in next class okay yeah thank you.