Design of Mechanical Transmission Systems

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Week – 09

Lecture – 25

Lecture 25_Brake: Thermal Analysis and Braking Conditions

Good morning. So, welcome back to design and analysis of brake systems. So far we have discussed about the various aspects of brake systems. In fact, we have done the brake working methods, brake types and the brake torque requirements and dynamic analysis. I am just giving a top headlines, in between we have discussed so many thing. So, today we are going to learn about a thermal analysis.

So, that is what we are going to focus the thermal analysis of brake system aspects. Before going to thermal analysis, I would like to show a couple of videos about thermal analysis aspect. You can see this is the Honeywell Dunlop Alliance, over weight landing aspect how the brake is going to be applied. You can see this is brake test.

You have to simulate exact running condition as when flight is running on the runmat or runway that is a cooling air. Look at this portion completely fired right. So, that much energy is developed and you need to understand that in aircraft we will have a multiple disc brakes. There is so many we need because of we need a more friction when you want to have more friction you need to have more surfaces. So, we will have a multiple disc brake that too carbon-carbon type is there.

So, that is the advanced study, but since this is design aspect we focus more of automobile aspect. This is the one video you would able to see the how exactly the energy is dissipated while applying a brake. Look at this how much energy right, the entire aircraft weight that energy need to be converted into friction energy that is one thing is there. Then I would like to show the another video which is taken from the Ferrari. This is called test speed right. They have taken the test speed look at the noise hear the noise. And now you can see the wheel right did you see that there is a red flame is coming right that is coming because of the heat aspect. So, maybe I will share this complete video later this disconnected. Then the another one this is for the. This is the Boeing. The new Boeing 747 dash 8 is a massive machine designed to take off at close to 1 million pounds. Through months of flight testing the airplane is shown plenty of power on take off, but how would it handle all that energy if it had to suddenly stop. In the emergency event that we have to make a rejected take off at these heavy weights it takes a long distance for the airplane to stop. It is just like in your car. Captain Kurt Vining and the Boeing test and evaluation team are about to put the airplane through the ultimate rejected take off for RTO.

First the crew installs a set of 100 percent worn out breaks. So, it is down to the studs so if you ever have your own breaks they have got a machine down so there is this basically no material left. Technicians also fuel the airplane up to maximum take off weight of just over 975,000 pounds. At the start of the runway Captain Vining begins the take off role as usual, pushing all 4 engines to maximum thrust. But just as the airplane is going at over 200 miles or 320 kilometers per hour he slams on the breaks.

To channel maximum energy to the department breaks the pilot cannot use the thrust reversers. You can see the flaps. Not being the brakes. The brakes made by Goodrich do exactly as they are supposed to. In fact the 747-8 stops earlier than the team had hoped beating the target by more than 700 feet or 200 meters.

Look at the smoke you can see that. But stopping is just half the challenge. Now the airplane must prove it can withstand the tremendous heat that built up in the wheels. Estimated to be more than 1400° C. Can you see the flame here? And it is a simple physics problem.

We have to turn that kinetic energy into heat in the brakes. As expected smoke pours out from the brakes as they glow a bright orange. Still the firefighters who are standing by can't do anything but watch for the next 5 minutes. That's to simulate that if you were in an airport and you had an RTO you wouldn't necessarily have the fire department right there. So you demonstrate that worst case would be 5 minute response time for a fire department to get to the airplane.

By design special fuse plugs in the tires are activated deflating the tires before they explode. Finally at the 5 minute mark firefighters move in with plenty of water. While the tires and breaks will have to be replaced the rest of the airplane is perfectly fine. No sweat even for the flight test engineers who were on board. It went amazing. The decelerate was exactly what we expected. Brake stopping no major faults. Slamming on the brakes so the new 747-8 can continue moving towards certification and delivery. Yeah so you could see that so right the brake test is very expensive one. It's not that easy and you have to have lot of money involvement right.

It's money and time involvement is there. So and also it's very stringent because it involve with the human life. So the reliability is very critical. It has to go through various standard stringent standard for the break application. I am talking about general automobile. If it's aircraft it even more severe right. So it's even more severe. So that's it. This is the reason we need to understand about the thermal analysis. The one question I would like to ask okay.

What do you think about the stresses caused by heat? Which is it more than the structural stresses or will be equal? Why we should give importance to thermal analysis? That's another question okay. And also I would like to ask a question. How do sizing your brake right? Sizing earlier we have discussed about the balancing of the energy right. Torque coming from the break pedal too right. And also we have chosen the right friction lining or break lining.

That's we have done that. Apart from we have to take care of the thermal analysis also okay. We will be go into details now. So we can see that this is the disc brake which is glowing very readily during the application break application yeah. So the purpose of the thermal analysis due to determination of friction by temperature that is the important thing. And also to understand thermal stresses are developed in the break system.

So when you say thermal stresses is talking about not only your friction lining of brake and also the counter which is the rotor both both parts. That's why it's a pair friction pair yeah. And the temperature of the brake fluid and finally the temperature of a seals, bearings and surrounding components because those components are affected due to breaking as the temperature rises. When the temperature rises that obviously through conduction, convection it's going to spread around the component. I am talking about the seals, bearings, surrounding components within the break system which going to affect the their performance also right.

And thermal effect. So as I said the thermal stresses are greater than the mechanical stresses. Very high. Very very high okay. Very high and that give coning gives rise to there is a one there is a one effect is going to come it's coning. Well discuss in figure what is that mean.

That will increase the pedal travel, increase the taper wear and more importantly will give uneven input which is called hot spots. It's called hot spots and and if look at this is the normal your disk, you can see that. As the break is subject to thermal thermal or heat it's going to have a this is called coning.

Can you see that? It's like a hat. When you have a hat you have a rim. The rim instead of flat it goes to this way. So that's why like a crown or cone that kind of shape is there. That's effect you would expect. The another effect also you can see that the hard disc with the undercut you can see there is a undercut the things also. These are two things experienced in brake system due to thermal stresses. And one more information okay because of this the stiffness is going to be affect. You need to have a very stable structure element right. So it should be hold rigidly right. That's also you don't want to have a changing the stiffness aspect.

Yeah and you can see that as when you apply the brake pads right onto the rotating disk due to thermal what you see the observation here? The wear will be won't be uniform. In fact they will be tappered. So when the tappered again that's going to affect the performance of the break. So this is again due to your coning aspect.

You can see that. We will have a very uneven. So with the moment uneven as wearing out finally the the whatever the supporting pad will rub against the rotating disk. That's need to be avoided. Yeah that need to be avoided.

And let me ask question. So what are the possible way to test the brake? Do you know any standard methods? How to test a brake performance? Any idea? Yeah any idea? Will you test, I am sure when you drive a two wheeler or four wheeler you keep usually will keep it right half way through. That is not the way to do that right. When the moment you want to apply brake you have to apply brake.

That's fine. That is the way need to do. But question is how will you test and what condition you do that okay. So before that I will talk about disk material also. The thermals is again very greater in the disk material compare due when compared to mechanical stresses. So you have to understand the whatever heat generated that should not stay in the contact.

The moment stays that's not good right. It should be dissipated. That means the material the friction lining material, the corresponding the rotor or disk need to have a high thermal conductivity. So in order to maximize the thermal conductivity the material disk material can be have a different composition either can have a graphite flex structure, high carbon, cast iron. In fact I said when you use aircraft usually go for a carbon-carbon composite because the temperature is very high.

So when you have a high temperature so the material should withstand the high temperature not only to withstand and also should able to dissipate. Both ways you need to look at it yeah. And the silicon, titanium, vanadium, copper, molybdenum also using used to enhance the thermal conductivity. Ferrite and pearlite different characteristics also can be used. These are the four methods where used to improve the thermal conductivity right.

So we will talk about before going to the thermal analysis, we will discuss about what is the need of the thermal analysis in brake okay. As I said you have to fix your brake sizing. That is one important and design optimization and material suitability for this much energy this is the right material to withstand when you talk about right material. I am talking about the friction lining material and the corresponding disc and also the both material aspect okay. The material suitability, the brake friction performance okay, prediction aspect, component fatigue and wear life. When you talk about component fatigue and wear life we are talking about break fading okay. We will discuss what is the mean brake fading. And more importantly the breaking cooling and influence in factors. So these are the few important factors are need to be considered for the thermal analysis okay. And one more important is NVH. NVH is nothing but noise, vibration, harshness okay. You have seen the video right how much noise coming right. So do you think that is comfortable for human ears? No. So you have to minimize the called squeal, breaking squeal that is the sound effect that has to be minimized. So these are the things need to be addressed while doing thermal analysis right. Brake fading right. The brake fading nothing but a reduction or loss in braking force due to loss of friction between the disc pad and the rotor.

Fade away you know when you have showed, this you can after wearing some certain period, you will say the color is fade away. Same phenomena right. Fade is nothing but heat build up through the repeated and prolonged brake application that is called brake fade. So by if you have brake fade, its friction development will be reduced obviously because of that the performance of the brake also reduced. May be you could see there is a you can see this is a disc brake right.

You can see this is a disc brake. So what do you what do you observe? There are nice dark patches. What do you think of them? What do you understand that? What are they? These are the hot spot. Remember one lecture I clearly mentioned which as a lighter way when you make chapati right and give the heat right uniform heat and flip it on the other side you will see the dark parts right because that is a localized heat developed right. So the moment you have localized heat developed what do you expect? Microstructure changes. The moment is microstructure changes the hardness will change.

When the hardness is changed what happen to the this sticking thing right the friction obviously that is going to be affect. So you could see that how the hot spots also play a vital role with respect to brake fading aspect right. So this is what I asked how do you test the braking? What is the way to test the braking? Okay right. You can do a single stop braking application that is one type. Second one is it is called repeated brake application. The third is called continued or drag brake application. Three way you can test the brake. We will discuss one by one. Single stop braking okay. Single stop braking is nothing but so what you have to do you raise the speed of the vehicle to the top speed and apply a brake that is it right. Single stop brake application from wheel top speed to zero with the high deceleration represent very severe braking duty with the maximum kinetic energy to be disappears into the disc and drum interface. I am talking disc and drum but they are interchangeable and the brake lining okay. So single stop braking means you allow the vehicle to reach the maximum speed, apply a brake and see what is happening right. So that is the severe braking duty, very severe braking duty with the maximum kinetic energy to be disappears into the disc and brake lining okay. So just emphasize when you talk about disc, drum they are interchangeable in our discussion. So the high heat generation the braking time may be less than the time required for the heat penetrate through the drum and disc material. So what do you understand? What will be the braking time? When you apply a brake you know you raise the speed to the maximum apply a brake. So what will be the braking time? Right. Usually braking time in few seconds, few second. So do you think the heat by a time the heat will be penetrated to the disc and the brake lining? Do you expect any cooling aspect? There will not be any cooling. There will not be any cooling but entire energy try to be absorbed within the your drum and friction material. So you can see that no convective brake cooling and almost 80% of brake energy goes to the drum right because it is happening such a short distance a short time I am sorry it should be such a very short time it is happening okay. So this is the single stop braking. Then repeated braking. So in the repeated braking instead of in the single stop you raise the speed to maximum and apply a break. Here is not like that. So here what you do that you at one speed you will raise the vehicle speed then apply a brake to the either 0 or some mid speed again increase the speed. In fact, I can tell you a vehicle is decelerated at a deceleration and the speed is increasing from a test speed to from whatever the speed you want to fix it to the next lower speed or 0 speed after which the vehicle is accelerated again to test speed and the braking cycle is carried out. This is called repeated breaking. Probably I will explain maybe in this direction okay assuming that this is my time. This is time duration. This is the braking cycle assuming that this is the braking cycle yeah. So what happened? So this is braking speed I would say that this is the braking speed. So initially you this is the maximum speed and I want to do the lower speed okay. So initially I will apply a brake then bring it down to the vehicle like this right. The moment it reach to the lower speed what I am going to do I will again accelerate. Again accelerate to reach the maximum speed then apply a brake bring it down the speed to the next speed. This side the n_{max} you can say that n_{max} and $n_{minimum}$ something like that right.

So again do that. So what do you understand? By doing that I am accelerating to one fixed speed and bring it down to the lower speed again accelerating and decelerating, accelerating and decelerating. So what do you expect in repeated braking? Is there any cooling? There is a cooling right. We are allowing the system to cool down right. We are allowing the system to cool down okay. So in this the brake pumping involves repeated break application from one single speed to until the vehicle speeds.

So the brake pumping is a technique that sometime used in the slippery condition to allow the vehicle to unlock so that the vehicle stays somewhat straight during the stop okay. This is for the repeated braking. Now we will move on to the third one is called continued or drag braking okay. Continued or drag braking means when the vehicle moves in the slope right, this is I am talking about this is the θ right and you can say this is your the height of the thing. So the vehicle it is a downhill right. This is downhill right. So when the brakes are applied during the long down wheel design, cooling while braking must be considered while braking must be considered. This also part of the brake regulation and more specific to heavy commercial vehicles because they will carry the huge load okay. Let me ask question. When you move slope, how will you apply the brake? How will you apply the brake? Okay. So the difference the previously we have discussed about the repeated brake. When you say repeated brake, it makes certain speed, bring it down to certain speed. Again accelerate, decelerate, accelerate, decelerate. That is called repeated. That is repeated. Here we are discussing about the continued. What do you mean by continued braking? You have to keep applying a brake. You have to keep applying a brake. What is that mean? So let me ask question. Assuming that you are not applying a brake, you are moving downhill. If you leave it as it is, what happen to your vehicle? Yes.

It is accelerate right. It will accelerate. It is due to gravity. That is what is happening. So how do I maintain that? You have to keep braking right. It is called another time it is called clutching also. In the clutch also there will be there. You have to continue breaking until you have a control the motion of the vehicle safer right so that to stop the vehicle.

Are you going to stop the vehicle? No right. You have to control the motion of the vehicle because it is moving or descending from the top to the bottom through the slope or downhill. This is what happen. So because the vehicle will undergo all this all this phenomenon, it goes to the on the level plain road and also it has to go to the uphill, downhill all those things. So when the vehicle is going all the situation, you have to test the braking performance also for the all the conditions. That is why we say that single stop braking, repeated braking, and third one is continued or drag braking okay.

So this is what we are going to discuss in thermal analysis. See in the design we always talk about torque right. We always talk about torque. In thermal analysis what term can we use equivalent to torque? Heat flux or can we say energy right. So here instead of a brake torque, we will say brake energy.

We will use more of brake energy, brake power. They are the same but only thing is since we talking about the heat transfer aspect, a thermal effect, so that is how we need to use the terms. Okay there is a please understand okay do not get confused. They are the same. Only thing is application wise, we are changing. One is for the structural aspect. Torque is a structural aspect whereas your heat flux or thermal energy or brake energy or brake power with respect to thermal aspects okay. The energy input for braking aspect two terms as I said brake energy and the brake power we are going to discuss. Yeah I will derive some equations okay. So assuming that we have a vehicle, vehicle is decelerating on a level surface from V_1 speed to V_2 speed okay. When a vehicle decelerates right on a level surface from V_1 right to V_2 speed, then the brake energy.

$$E_b = \frac{W}{2g}\left(V_1{}^2 - V_2{}^2\right) + \frac{I}{2}\left(\omega_1{}^2 - \omega_2{}^2\right)$$

Where W is the weight of the vehicle in N

V_1 is velocity at beginning of braking in m/s

V_2 at end of brake in m/s

I = mass moment of inertia of rotating parts in kg-m^2

ω_1 = initial angular velocity of rotating parts.

ω_1 = end angular velocity of rotating parts.

So what will be the brake energy? The kinetic energy of the vehicle right that is the one energy you will have it. Any other energy you expect? Yeah. Any other energy? That is one energy right. What happen the initial energy due to rotating components? That is also come into the energy right. There is a some more energy. Your flywheel rotating, clutch is rotating, a gearbox also rotating right, and what else rotating? The wheels also rotating right. So what happen this rotating components? There also will give some more energy right. There also we have to account. So this is what happen okay. Where W is the weight of the vehicle in N okay. So V_1 is velocity at beginning of braking. That should be meter per second. V_2 at end of brake. So this is the velocity at the beginning of braking.

So this is the velocity at the end of brake in meter per second okay. So what is the I? Maybe I will use it in another slide. Where I equal to mass moment of inertia of rotating parts. So mass moment of inertia of rotating parts in the vehicle. That is a unit. Then ω_1 angular velocity of rotating parts. So this is the mass moment of inertia of rotating parts initial angular velocity okay end angular velocity of rotating parts. This is what happening okay. So I rewrite the equation

$$E_b = \frac{W}{2g}\left(V_1{}^2 - V_2{}^2\right) + \frac{I}{2}\left(\omega_1{}^2 - \omega_2{}^2\right)$$

The question is when the vehicle stops what happen to your speed? V_2 will be 0 right. When vehicle stops initial velocity at breaking V_1 then corresponding rotating angular velocity ω_1. The moment it stops the vehicle stops the V_2, ω_2 will be 0 right. V_2 equal to 0 corresponding ω_2 equal to 0 okay. And we know there is a equation right because I want everything convert into one combined equation. What you understand R_w? R_w is the radius of the wheel or tire equal to what you expect? In the relationship you know V equal to $R\omega$

right.

$$V = R_w \omega$$

This is the way you can take it out right. So when you have V_1 can have $V_1 \omega_1$ also.

$$V_1 = R_w \omega_1$$

So when you substitute this thing you would expect this generally

$$E_b = \frac{W}{2g}\left(V_1{}^2\right) + \frac{I}{2}\left(\omega_1{}^2\right)$$

Can you substitute please? Yeah instead of I remove the ω_1 I want everything with respect to V_1. So I will be there I will be there right

$$E_b = \frac{W}{2g}\left(V_1{}^2\right) + \frac{I}{2}\left(\frac{V_1{}^2}{R_w{}^2}\right)$$

I by 2 instead of ω_1 square I will have a V_1 square right V1 square by R_w whole square that is there. Yeah. So V_1 square common here even I want to take out the vehicle's weight also separately by doing that the entire thing I want to take it out. When you do that so I would expect

$$E_b = \frac{W}{2g}\left(V_1{}^2\right)\left(1 + \frac{I}{R_w{}^2} \times \frac{g}{W}\right)$$

$$E_b = \frac{W}{2g}\left(V_1{}^2\right)(K_m)$$

the entire thing is termed as a K_m. K_m is nothing but correction factor

$$K_m = \left(1 + \frac{I}{R_w{}^2} \times \frac{g}{W}\right)$$

So this is correction factor of rotating masses masses okay. Remember I think we have initially in the break we have done one problem, we have taken for a rotating parts take 5 percent energy of the total kinetic energy that is what we said. Normally the K_m will be changed from 5 to 15 percent of total kinetic energy of the vehicle total KE of the vehicle okay.

Now understand that the K_m also very important. So in fact the when we derive the equation for the balancing of the friction and lining there also we have discussed right K_m is the correction factor the same this is the correction factor yeah. So this is the velocity okay this is finally we got the brake energy now I need to find out the brake power the braking power is required to find out the brake power. Or equal to okay just want to brake power is equal to rate of change of brake energy during the breaking. So what I am going to do that just want to do this is BP it is a brake power is nothing but

$$BP = \frac{dE_b}{dt} = \frac{d}{dt}\left(\frac{W}{2g}{V_1}^2 \times K_m\right)$$

this is the general equation. Ultimately we need to find out what will be the brake power yeah. So this is the equation we already assume that the vehicle is moving on the plane surface right. So what happen if you have deceleration is constant what happen what do you expect? So this is the equation if the deceleration is constant then the velocity of the vehicle what happen

$$V(t) = V_1 - at$$

this is the equation. So I am going to substitute this one into the my brake power. So instead of V_1 I will take it as a V_1 minus a t this is the equation you will get it yeah.

$$BP = \frac{dE_b}{dt} = \frac{d}{dt}\left(\frac{W}{2g}(V_1 - at)^2 \times K_m\right)$$

$$BP = K_m\left(\frac{Wa}{g}\right)(V_1 - at)$$

I think square term because of the V_1 square right this is square term. So when you integrate and simplify that finally you are expecting the equation would be V_1 minus a t. So this is the equation you are getting yeah. So this is the equation you are expecting. So this is your brake power, you would expect for the vehicle things okay this is the brake power.

So now what I want to say that so when you apply a brake right that braking time t_b will be what you expect the t_b brake time

$$t_b = \frac{V_1}{a}$$

t_b = braking time(sec)

t b with respect to V 1 by a that is it V 1 by a right. Then we can take it as a equation number one where t b equal to breaking time suffix b is the for braking time that is in seconds please remember this in seconds not in minute or anything right. So the brake power right I will take it as a average brake power okay.

$$BP = K_m\left(\frac{Wa}{g}\right)\left(\frac{V_1 + 0}{2}\right)$$

$$BP_{av} = \frac{K_m}{2}\left(\frac{Wa}{g}\right)(V_1)$$

So I have taken the average when you have taken the average in the sense from the power will change the moment you apply brake that when that power will be there the power will be maximum right there power will be maximum okay. The moment the vehicle stop the power will be 0. So when now you do the calculation you have to go for the average break energy aspect that is why I have taken the average the V_1 plus 0 by 2.

So this is your brake average brake power for any given vehicle when moving at the plane surface. I think I will stop now. So other things I will discuss in tomorrow lectures.