Chapter 3

Implementation

3.1 Linear force on the pad

In the present section, the linear force that must be applied on the pads to slow down swiftly a car will be evaluated. The present work concentrates on designing an e-caliper for the front brakes only because they account for roughly 70 % of the total deceleration force produced during slow down. Therefore, if such an e-caliper can be developed for the front brakes, it will be a breeze to adapt it for a rear setup.

For this calculation, the dimensions of a Renault Espace Zen[1] are considered. This is a fairly large and heavy car with a curb weight of 1735 kg and the typical kind of vehicle which could avail from an EMB system.

As mentioned earlier, the physical principle behind a braking mechanism is to convert the kinetic energy of the moving car into thermal energy. The previous sentence suggests that we're talking about the linear kinetic energy. However, it's not the only kinetic energy that must be dissipated. Indeed, discs, wheels and shafts are rotating masses and possess therefore an angular kinetic energy. Lastly, if the car is a front-wheel drive, the rotational energy of the entire transmission has to be dispersed. It's worth noting that during the deceleration, when the driver's foot is off the throttle pedal, the thermal engine acts as a mechanical resistance that helps slowing down the car (due to the gas compression in the cylinders). However, in the present calculation, this resistance is not weighted in to consider the worst case scenario possible. Also, the car is assumed to drive on a flat surface (no potential energy involved).

The first step consists in determining the so-called equivalent mass[2] of the car. Indeed, calculating the rotational energy of the transmission is very complicated as many parameters come into play and the geometry and materials of all the rotating components must be known. Therefore, a generic formula to get a rough approximation will be used instead. Experience has shown the total equivalent mass of a typical car can be estimated with the following engineering rule of thumb[3] :

$$m_e = m(1 + 0.04 + 0.0025 \cdot G^2) \tag{3.1}$$

Where :

- m_e is the equivalent mass $[kg]$
- m is the mass of the car $[kg]$
- $G = G_f * G_t$ is the total gear ratio with :
  - G_f the final drive ratio [/]
  - G_t the current transmission ratio [/]

The gross weight rating of the Renault Espace Zen is 2353 kg. If the final drive ratio G_f is 3 and the car is currently driving at 130 km/h in 5th gear (G_t equal to 0.8), the equivalent weight is :

[1]Retrieved on February 27, 2018 from `https://fr.renault.be/vehicules/vehicules-particuliers/espace/versions-et-prix.html`

[2]Please, consult the annex B to read a detailed explanation of what the equivalent mass is.

[3]Retrieved February 28, 2018 from `http://hpwizard.com/rotational-inertia.html`

$$m_e = 2353 * (1 + 0.04 + 0.0025 \cdot (3 \cdot 0.8)^2) = 2481\ kg \tag{3.2}$$

The total kinetic energy E of the car is therefore :

$$E = \frac{1}{2} \cdot m_e \cdot v^2 = \frac{1}{2} \cdot 2481 \cdot \left(\frac{130}{3.6}\right)^2 = 1.53\ MJ \tag{3.3}$$

If the maximum deceleration the braking system can produce is 1.2 G, it means the car will slow down from 130 km/h to 0 km/h in :

$$t_f = \frac{^{130}/_{3.6}}{1.2 \cdot 9.81} = 3.07\ s \tag{3.4}$$

And will travel during that time the following distance :

$$B_d = \int_0^{tf} a \cdot t^2 dt = \int_0^{3.07} 1.2 \cdot 9.81 \cdot t^2 dt = \frac{11.77 \cdot t^3}{3}\bigg|_0^{3.07} = 113.52\ m \tag{3.5}$$

Note that this braking distance is realistic only in the scenario of a dry road. In that case indeed, the coefficient of friction between the rubber and the asphalt is around 0.6. The coefficient quickly drops when the road is wet however. The formula linking the coefficient of friction, the speed and the stopping distance is the following :

$$B_d = \frac{v^2}{2 \cdot g \cdot \mu} \tag{3.6}$$

With a coefficient $\mu = 0.6$, the braking distance B_d is 110.77 m but if the coefficient drops to 0.4, the stopping distance increases to 166.16 m.

Let's calculate henceforth the linear braking force at the contact tire/road. Let's hypothesize that the braking distribution between the front and rear brakes is 70 % – 30 %.

The linear force times the distance (the work generated by the brakes in physics terminology) must equal the kinetic energy of the car. Therefore, the total linear force L_f is :

$$L_f = \frac{E}{B_d} = \frac{1.53 \cdot 10^6}{113.52} = 13.47\ kN \tag{3.7}$$

And the linear force at one front wheel F_t (Figure 3.1) is :

$$F_t = \frac{Lf \cdot 0.7}{2} = 4.72\ kN \tag{3.8}$$

Let's determine now the resistive torque that one front brake must be able to generate. If the wheel rim is 17″, the tire's cross section 235 mm and the aspect ratio 65, the outer diameter of the wheel is : $D = 17 \cdot 25.4 + 235 * 0.65 * 2 = 737.3\ mm$. The torque T_b is then easy to find :

$$T_b = F_t \cdot \frac{D}{2} = 1.74\ kNm \tag{3.9}$$

As the front disc diameter is 320 mm and by assuming the pads are 40 mm high, the mid-point of the pad that does contact the disc is located on a circumference of diameter $d = 280\ mm$. The linear force at the point of contact disc/pad (F_d) that has to be generated is :

$$F_d = \frac{T}{r} = \frac{1.74 \cdot 10^3}{140 * 10^{-3}} = 12.43\ kN \tag{3.10}$$

If the coefficient of friction between the pad and the disc is 0.35, the force required to push the pad is :

$$F_p = \frac{12.43 * 10^3}{0.35} = 35.51\ kN \tag{3.11}$$

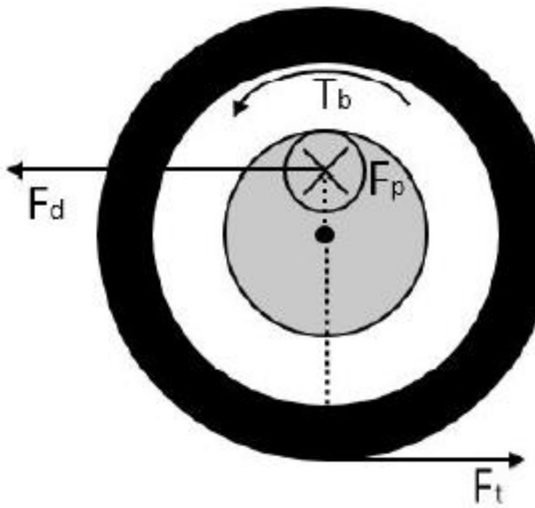

Figure (3.1) – Forces at stake in a wheel-disc system

As brakes are safety critical system, let's apply a safety factor of 1.5 and consider the force that the system must be able to generate to be :

$$F_p = 1.5 \cdot 35.51 = 53.26\ KN \tag{3.12}$$