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DYNAMIC LOADS ANALYSIS FOR SPRING BRAKE PADS APPLIED ON COMMERCIAL VEHICLES

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Abstract. *The proper acting of a brake system depends on different components and accessories beyond the brake pads and caliper. Most of these accessories are metallic and contribute to the brake's application, installation, and assembling, therefore all accessories need to be correctly designed through specific tests and measurements. During the vehicle's application, several conditions and imperfections of the roads generate different dynamic loads, mainly accelerations, that are transmitted directly to the brake system, which has no suspension attenuation. Vibrations directly affect brake pads, which can be thought of as an inertial mass inside the caliper. The movement of this mass is undesirable, thus, the brake springs are highly important components on the brake pads field application, since the minimum required force to cause movement is increased by them. This type of component has several functions: compensating for system's clearance; decreasing vibration when going through obstacles; and avoiding misalignments during movement of the brake actuation. The present study aims to understand the dynamic loads which springs are exposed to in field application. Once the dynamic loads are known, it's possible to design better bench tests used for spring's evaluation, as well as to define their minimum mechanical properties requirements, thus, reducing the time cycle for developing a new brake pad. Results of an instrumented route of a city bus are shown, where: axle acceleration, pad temperatures, brake pressure, among others were acquired. In addition, some spring data (like temperature and extensometry) was acquired. All of this field data was correlated with bench tests data, in order to define the levels of force to which springs are exposed during application. Spring clamp force was correlatable with the inertial brake pads force when peaks of acceleration occurred due to road imperfections. Despite other dynamic effects not being taken into account here, the main mechanical load on springs is caused by the inertia of pads under acceleration peaks. The evaluated application of the city bus route, did not show critical spring temperature, brake pressure, and pad acceleration.*

Keywords: *spring brake pad, commercial vehicle, dynamic loads, road mapping, disc brakes.*

1. INTRODUCTION

Brake performance is a critical issue associated to vehicles safety and brakes design. In this way, brake pads are generally extensively studied and tested during the development cycle, however, there are several other components which can strongly affect the brake proper acting. Some of these components are caliper and metallic accessories, like springs. This accessory is important for compensating system's clearance; decreasing vibrations caused by road imperfections or going through obstacles; and avoiding misalignments during movement of the brake actuation.

Road roughness has been shown to present a Gaussian distribution and to be spread in a homogeneous and isotropic way over its entire span. Roughness models developed by Dodds and Robson (1973) show that by measuring a certain length of the road, it is possible to predict the behavior of the whole road, and thus calculate the maximum force a vehicle should face while traversing such road with a high degree of certainty.

The unsprung mass of a vehicle corresponds to all the mass of suspension, wheels, brakes, and other components directly connected to them. The work done by Hrovat (1988) has shown that since these elements are in direct contact with the road surface, they are exposed to the highest dynamic forces due to road roughness.

Brake pads are mounted in such a way as to restrict movement in all directions except radial. For this direction, a spring is used to guarantee a tight fit in the brake caliper, while also allowing some movement in case of high forces taking place on the pad. Springs applied on disc brakes of commercial vehicles equipped with disc brakes are usually installed on the top of the backing plates. In order to keep the springs under compression during field application, the pad retainer compresses them against the caliper housing.

The forces applied by the road to the tire are transferred to the wheel and then to the entire braking system. Depending on the direction, such forces may cause brake pad undesirable movements. Pylypchuk, Chen, and Moshchuk (2014) have shown the acceleration that a tire is subjected to, might be measured indirectly, by the placement of strain gages in different parts of the vehicle suspension. These authors showed unsprung mass elements follow a similar acceleration pattern during vehicle application. This fact allows for easier instrumentation of this area, since a sensor can be positioned in such a way as to avoid difficult measuring conditions (like rotating or high temperature elements).

Forces caused due to road roughness are the main forces that can cause deflection on pad springs, and these forces may be measured indirectly in two ways: through measuring the acceleration of unsprung mass during a normal application, or through measuring the spring force directly. According to Rohrbach and Lexow (1986), miniature force transducers are widely used in applications that are space restricted, or force capped. Measuring the force in a brake pad spring is a difficult task due to space limitations and temperature conditions, but by using miniaturized parts (such as strain gauges), this task becomes easier and more robust.

Other factors may also have an impact on the spring force. Fieldhouse *et al*. (2006) have shown the center of pressure over the pad during normal operation may fluctuate. Such changes may result in a torque on the normal plane of the braking pad, and since the pad is restricted on all sides except for spring side, this torque may be felt as a force on the spring. Such force would not be captured by measuring the acceleration of unsprung mass, but would be seen on a strain gauge.

Extensometry measurements are fundamental tools in engineering, since they allow to perform strain measurements. As shown by Antunes and Masotti (2017), high errors on strain measurements can be caused by high strain gradients and by transversal effects on strain gauges, leading to errors around 20%, with no temperature effects. Gabauer (2000) showed a methodology for determining the uncertainties related to the strain measurements on a tensile testing. This author showed a confidence level around 68% for the combined uncertainty of several sources.

This work aims to understand the mechanical and thermal loads actuating on springs of brake pads during application. For that, the main operating conditions of a typical city bus route need to be measured by several instrumentations, such as temperature, pressure, and acceleration. Thus, there is a focus on the measuring of the dynamic loads to which springs are submitted. Once these loads are known, it's possible to design better bench tests used for spring's evaluation, as well as to define their minimum mechanical properties requirements.

2. METHODOLOGY

The methodology of this study was divided into two stages. The first one is the calibration of the springs, performed on a universal test machine, where values of displacement, force, and strain of each spring were correlated. The second stage consisted of vehicle instrumentation in order to collect values of brake pressure, brake temperature, axle acceleration, and spring strain. The spring strain data was correlated with the calibration values to understand the mechanical loads of the spring during application.

2.1 Springs calibration

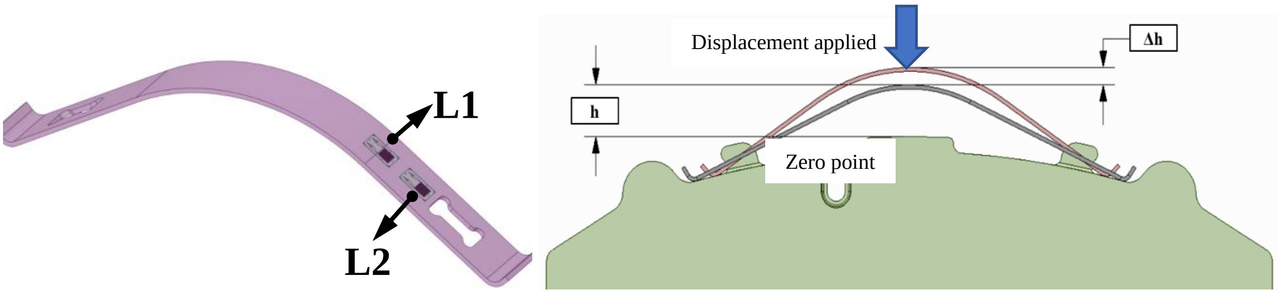
Several measurements on springs were performed before the vehicle instrumentation, in order to enable a later correlation of force, displacement, and strain according to the levels of application loads. Thus, the springs themselves were used to accomplish the role of "load cells" for the mechanical loadings on field tests. Table 1 shows the measured characteristics of calibration and field tests.

Table 1. Measured characteristics on both steps of the study for springs.

	Displacement [d]	Force [F]	Strain [ε]
Calibration (bench test)	✓	✓	✓
Field test			✓

The calibration was performed on a universal test machine, where both springs used on the vehicle during instrumentation were calibrated separately – one spring was applied on the inner right rear brake pad (IRR) and the other was applied on the outer left front brake pad (OLF). Both springs had two extensometers – L1 and L2 – according to Figure 1 (a). The procedure starts by identifying the "zero point" on the top of the backing plate. Then, the spring is assembled on the top of backing plate, allowing the spring force response measurements, as a function of the displacement from the top of backing plate, according to Figure 1 (b).

Prescribed displacements were applied, starting from the spring top, until very close to zero point. The universal test machine registered displacement and force during the entire test, while, the strain measurements on both extensometers were collected by an HBM Spider 8 and Catman Software. Thus, displacement, force, and strain could be correlated.



(a) (b)

Figure 1. (a) Extensometers position L1 and L2. And (b) Measurement of spring response force.

2.2 Instrumentation/field test data

A partner fleet of urban buses equipped with the brake set of interest was chosen, so the instrumentation was performed for one vehicle. In order to understand the dynamic loadings of the brake pad spring, critical run conditions were mapped for this kind of application, such as: A large amount of braking events, thus increasing the working temperatures of the brake; Runs with different drivers for evaluating different driving styles.

To perform the data acquisition, an MGCPlus from HBM and 15 channels, among pressure, temperature and accelerometers were used. Table 2 shows all signals collected on the vehicle, brake pad, and spring.

Table 2. Acquired signals.

- Pressure:	Front line Rear line	**Signals of the vehicle**
- Acceleration:	Front axle - X and Z directions Rear axle - X and Z directions	
- GPS:	Location system – longitude, latitude, altitude, and speed.	
- Temperature:	Outer Left Front [OLF] Inner Right Rear [IRR]	**Signals of the brake pad**
- Temperature:	Outer Left Front [OLF] Inner Right Rear [IRR]	**Signals of the spring**
- Extensometer:	2 gauges - Outer Left Front [OLF] 2 gauges - Inner Right Rear [IRR]	

Temperature for pads and springs was measured using thermocouples type K. For springs, thermocouples were welded to very thin copper sheets and were fixed using a high thermal conductivity paste. Later, they were covered with Teflon tape. Figure 2 (a) shows the thermocouple fixing and Figure 2 (b) shows the spring fixed on top of the backing plate and assembled in the caliper set.

(a) (b)

Figure 2. (a) Thermocouple welded to a copper sheet, fixed on a spring, and covered with Teflon tape. (b) Spring IRR and its components assembled on caliper set.

Data were collected from different runs of the same route in different day times, in order to encompass the variation of ambient temperature, different acceleration, and deceleration conditions according to rush hours and different amounts of people into the bus. The drivers were not informed about the instrumentation, avoiding any uncommon behavior, which could change the real brake condition.

The instrumentation spots – OLF and IRR – were chosen based on prior durability tests performed on this type of application, once the brake pad wear is mainly related to higher service temperatures. Even if the thermal load is equally distributed on the four brakes, it is known that each brake pad position is subjected to different temperatures. Rear brakes and inner pads are exposed to lower ventilation flow, working longer on higher temperatures than the front brakes. Likewise, the right brakes are more susceptible to higher temperatures, as this type of vehicle uses bus lanes for long distances and generally uses the right lane, contributing to the increase in brake working temperatures.

3. RESULTS

This section can be divided into three different sections. First, all the route characterization will be shown, where all data collected through the instrumentation channels will be analyzed. Second, the results of spring calibration performed on a bench test will be evaluated. Last, data from instrumentation and spring calibration will be correlated, in order to understand the dynamic loads of the spring, and also compare with inertial calculation results.

3.1 Route characterization

Route characterization consists in understanding the route relevance, in terms of brake application pressure, pad and spring temperature, axle acceleration, and spring strain. These characteristics were evaluated for five performed runs, at different hours. The route starts at a suburb neighborhood toward downtown and goes back to the same suburb neighborhood at the end. It is about 33 km long and usually takes about two hours to be covered.

3.1.1 Pad temperature and brake pressure

The temperature profile was evaluated for both instrumented pads – OLF and IRR –. The IRR pad is the critical one, being exposed to higher temperatures and it is shown in Figure 3.

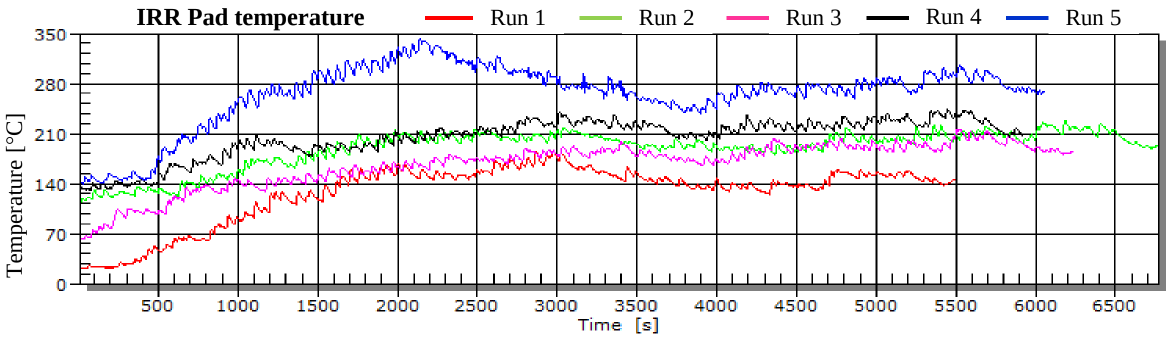


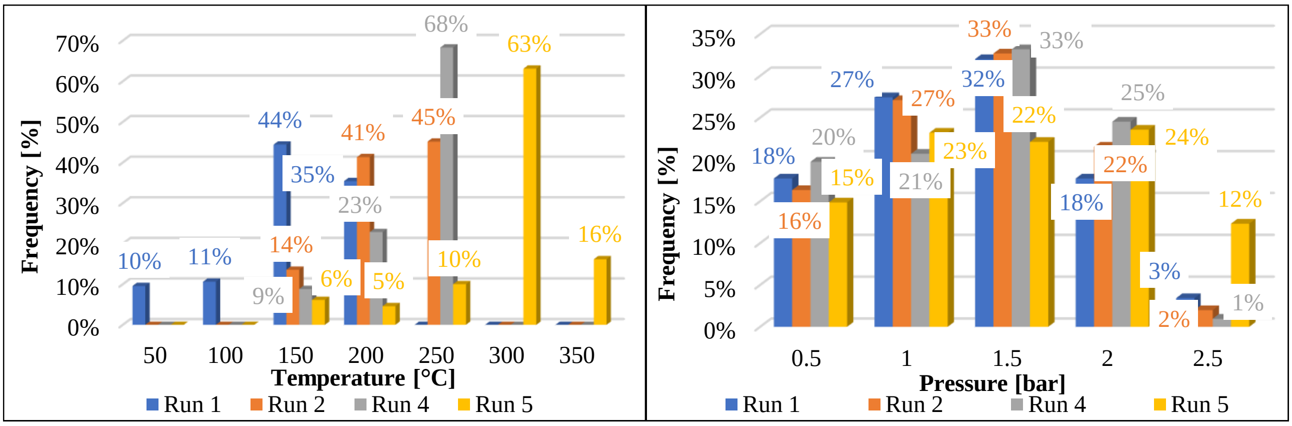
Figure 3. IRR pad temperature.

According to Figure 3, it is possible to notice that at the beginning of the first run (red curve), pads are at ambient temperature – 15 °C –. After some brake events, the pad temperature increases and reaches over 140 °C. It was found that the temperature profile is very similar for the front and rear pads, considering the same run, although the temperature amplitude is different – higher for the rear pad and lower for the front pad – showing the coherence of the data collected.

The fifth run profile – blue curve – was the only run performed with a different driver – driver 2 –. Both pads showed a significant increase in temperature, where the rear pad achieved around 350 °C. This evaluation shows the importance of having data from runs with different driving styles.

Histograms are useful tools for evaluating temperature data. Thus, Figure 4 (a) shows the histogram for the pad temperature of all runs, while Figure 4 (b) shows the histogram for the brake pressure. It is possible to understand that run 1 showed the lowest temperatures, achieving the maximum of 200 °C. Runs 2 and 4 showed a very similar profile behavior, and temperatures were between 150 °C and 250 °C. For run 5, the pads were exposed to temperatures between 150 °C and 350 °C, remaining 63% of the entire time over 300 °C and 16% at 350 °C. The effect of temperature increase in the sequence of runs can be partially associated with the increase in ambient temperature occurring throughout the day, and the cumulative effect of thermal energy in the consecutive runs. However, it is noticeable – due to the significant increase in temperature and the long time exposed to it – that for run 5 there was a great influence of the driving style. Data from run 3 is not being used on the histogram, due to problems with data exportation.

Different from the temperature analysis, which took into account all the data collected, the pressure evaluation should consider only each brake event of the route. For this analysis, the rear brake pressure was chosen, once both axles should have a very similar behavior due to a brake balance of 50% for this kind of vehicle. It is possible to notice that most of the brake events were at low pressures – up to 2 bar –. For run 5 – which showed the highest temperatures – there was a significant increase of brake events at 2,5 bar, compared to the other runs.



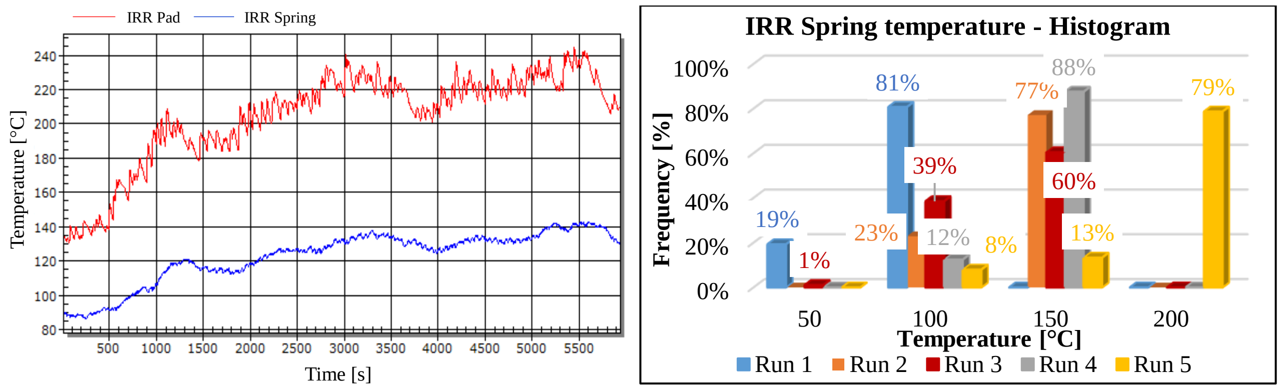
(a) (b)

Figure 4. Histogram for (a) IRR pad temperature; (b) brake pressure.

3.1.2 Spring temperature

Springs are the main object of this study, so the evaluation of its application's temperature is very important. Also, for the spring strain correct analysis, it is important to take into account the thermal expansion of the material, thus, the spring temperature evaluation is necessary.

Springs are exposed to lower temperatures than the brake pad, according to Figure 5 (a), which shows the comparison of brake pad and spring temperatures for run 4. It is possible to understand that the temperature profile is very similar for brake pad and spring, although there is a delta between them around 80 °C – 100°C. For a better understanding of the temperature levels for the spring, a histogram was built, according to Figure 5 (b).



(a) (b)

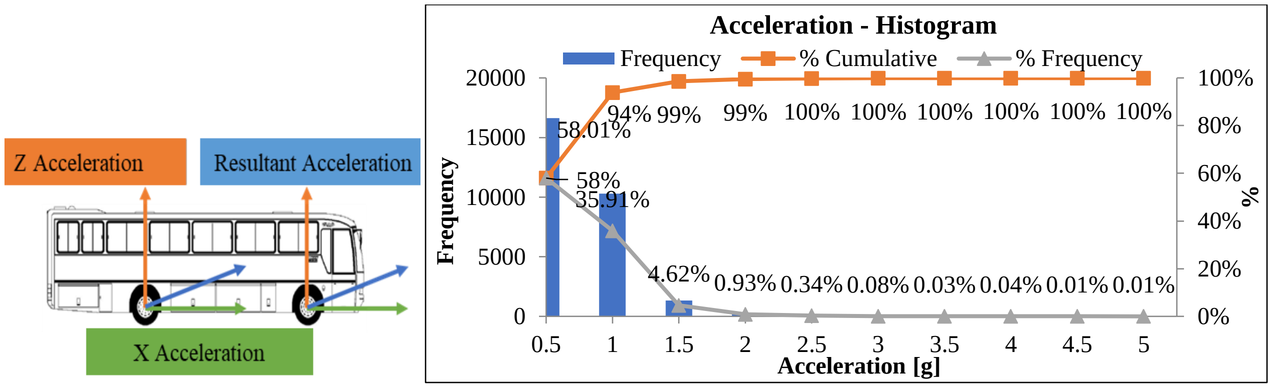
Figure 5. (a) Brake pad and spring temperature profile for run 4. (b) Temperature histogram for IRR spring.

The IRR spring was chosen for the analysis due to the more critical condition. According to the histogram, the application temperature of the most critical spring of the vehicle is between 100 °C and 150 °C, although for run 5 the spring was exposed to temperatures around 200 °C for almost 80% of the entire time. The temperature difference between IRR and OLF springs is up to 70 °C, showing how the IRR spring is more critical.

3.1.3 Axle acceleration

For the instrumentation, two biaxial accelerometers were used, one was fixed on the front axle and another on the rear axle, collecting the responses of X and Z axis, according to Figure 6 (a). According to the caliper position angle, the resultant acceleration was calculated, which was the normal acceleration from the top of the spring, and consequently, normal to the brake pad. This acceleration is the one associated with the pad displacement in the caliper, generating loads on the spring.

In order to understand the accelerations to which the system is exposed, Figure 6 (b) shows a histogram of run 5 for the rear axle, conditions considered the most critical ones. The histogram shows that 99,8% of the occurrences are up to 2,5 g's, and for higher accelerations, for example, 5 g's, there were only three occurrences, meaning 0,01% of the acceleration peaks. Evaluating this result, 99,92% of the field accelerations are up to 3 g's, being enough for the component approval.



(a) (b)

Figure 6. (a) Acceleration on X and Z axis, and resultant acceleration. (b)Acceleration histogram for rear axle – run 5.

To understand better the influence of the acceleration of the spring, and also the brake pad, Figure 2 (b) shows the assembly of the components in the brake caliper. After the spring is positioned on the top of the pad, the pad is assembled inside the brake caliper, and the brake pad bottom is supported by the caliper housing, restricting its movement. On the spring top, the pad retainer is assembled, which has the function of compressing the spring, generating a static installation load (measured as the spring calibration), avoiding any clearances and unwanted brake pad movements.

3.1.4 Spring strain

Spring strain during field test was collected for two reasons: to correlate with the results of spring calibration and understand the dynamic loads of the spring during application and also to correlate these dynamic loads with the force calculated by Eq. (2). If this correlation was successful, the dynamic load of any route could be calculated with only the axle acceleration data.

For the static installation force analysis, strain values were collected during the application of the pad retainer on the top of the spring. Applying the interpolation polynomial to correlate spring force vs strain – shown in the calibration results section – it is possible to obtain the spring force for this condition, according to Table 3.

Table 3. Static installation force for springs.

Extensometer	Installation Force [N]	Installation displacement [mm]
OLF L1	111.07	5
OLF L2	123.28	4
IRR L1	134.51	3
IRR L2	130.69	3.5

It was defined to be the static installation force, the lowest force between both extensometers, for this case OLF L1 and IRR L2, making this evaluation more critical. The difference found between both extensometers for the same spring can be associated with the fact the polynomial used approximates the force vs strain curve, but does not describe it exactly.

For this study, extensometers model 1-LY41-3/120 were used, at the ¼ bridge configuration. For this setup, there is no auto compensation for the strain caused by temperature, thus, it was necessary to apply Eq. (1), according to the extensometer datasheet.

$$\varepsilon_{(T)} = -19 + 1.88T - 5.22\,.\,10^{-2}T^2 + 2.37\,.\,10^{-4}T^3, \quad (1)$$

Where, $\varepsilon_{(T)}$ is the thermal strain, T is the temperature.

To perform the correct data analysis, it is only necessary to use strain values due to dynamic loads, and deformations due to thermal expansion of the material need to be disregarded. Thus, strain calculated with Eq. (1) was subtracted from the data collected during runs. For the initial period of the run, there is almost no difference between both strain values, although this difference gets more visible with temperature increase.

3.2 Spring calibration

For evaluating the spring calibration, the curves of force as function of strain were plotted according to Figure 7.

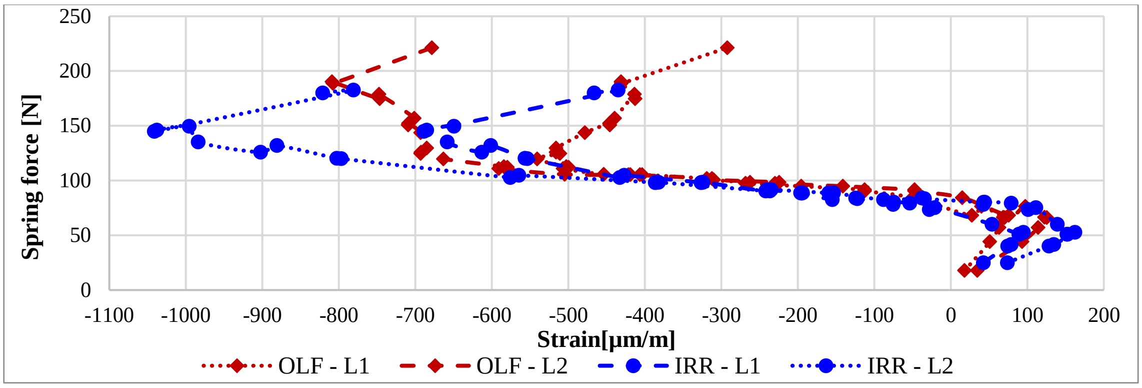


Figure 7. – Force vs strain.

According to Figure 7, it is possible to notice that both springs do not show linearity of force as function of strain. This behavior can be related to the spring shape and is mainly due to the contact area of the spring with the backing plate. The difference in force levels can be justified because springs are from different suppliers. Each extensometer is placed at a different position on the spring, so it is expected different results of strain for the same values of force.

3.2.1 Temperature investigation

Concerning spring exposure to temperature, according to the histograms shown in section 3.1.2, an evaluation of the spring force in different temperatures was carried on. A bench test was performed, very similar to the calibration setup, in order to understand if there was a reduction of spring force regarding the temperature increase. For this evaluation, springs were kept at a determined temperature for two hours, and then the force was measured while the spring was still hot. The temperature varied from 50°C to 300°C, and the displacement was measured from the non-deformed spring to 2 mm from the top of backing plate. Due to the high heat exchange with the environment, the spring surface temperature was measured during the force measurement, being considerably lower than the temperature of the heating oven.

For the spring application evaluated for this study, the installation displacement is 3.5 mm from the top of the backing plate, so force as a function of temperature was evaluated at this displacement, and also at 3 mm and 5 mm. Figure 8 shows the results of force for both springs, concluding there is no significant reduction of force due to temperature.

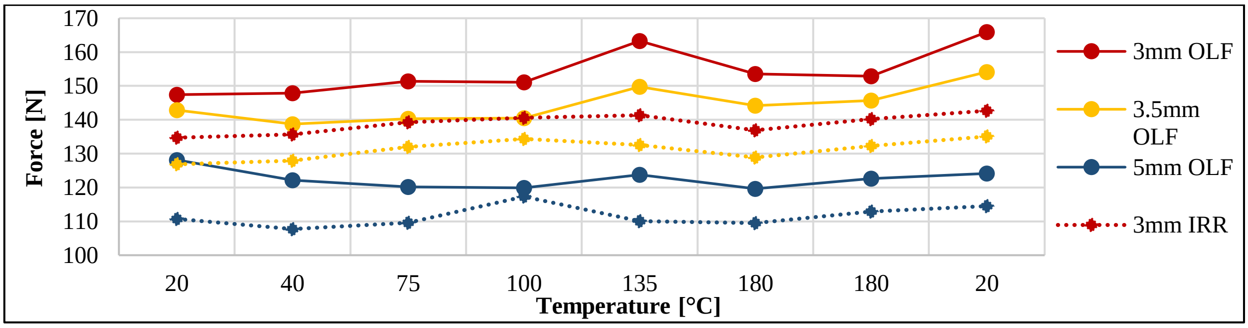


Figure 8. – Spring force as a function of temperature.

3.3 Correlation of force, strain, and acceleration

This section aims to correlate all the main information presented before, as spring force from calibration, strain, and acceleration collected from field data. First, an approach considering the calculation of spring force through inertial forces is shown. Later, the force estimation using strain values is presented. At last, the correlation of both approaches is made.

3.3.1 Force calculation through acceleration

One of the possibilities, and the easiest one, to estimate the dynamic loads of the spring during the application, is the calculation through Eq. (2), where the acceleration collected during runs and the brake pad mass are considered.

$$F = ma \tag{2}$$

Where F, m, and a are the force, mass, and acceleration respectively.

If the force calculated according to Eq. (2), is higher than the static installation force caused by the pad retainer (shown in section 3.1.4), the brake pad will move, otherwise, if the acceleration is low and the calculated force is lower than the static installation force, the brake pad stands still. Due to the restriction of the pad's movement imposed by the caliper, it is only possible for the spring to be compressed, there is no degree of freedom for spring expansion. Considering this approach, Figure 9 shows the static installation force for both springs (constant force), until the moment where the collected data showed an acceleration value which the calculated force was higher (peaks).

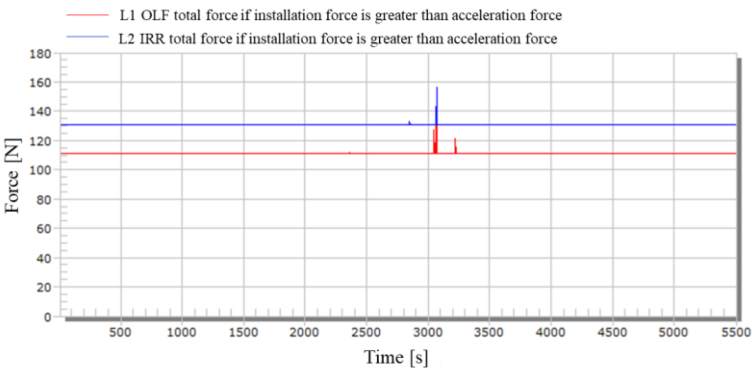


Figure 9. – Force on IRR and OLF springs, due to the installation force and calculated force.

During run 1, there were only two occurrences where the calculated force was higher, inducing a spring compression and the maximum force calculated was 158 N, on the IRR spring. The same approach was used for all runs, where two out of five runs did not show accelerations that would cause spring compression. Run 5 showed the highest accelerations, but only one peak was registered for OLF spring, around 166 N.

In order to complement this evaluation, the maximum acceleration to which the brake pad can be exposed without showing compression on the spring was calculated. For this analysis, the brake pad mass – around 2.6 kg – and static installation forces of both springs were used. The maximum acceleration with no spring compression was 4.35 g's for the OLF spring and 5.12 g's for the IRR spring. Comparing these values to the acceleration histogram, it is possible to notice that 99.98% of the collected data during runs showed lower values, meaning only a few compressive cycles would happen on the spring.

3.3.2 Force calculation through strain

Another possibility to estimate the dynamic loads of the spring during application is to use the spring calibration, where the values of strain measured on the field are correlated with values of the calibration curve of force vs strain. Thus, it is more important to focus this analysis on the strain range to which the spring is submitted during the application, from the installation position to higher compression, minimizing errors of the polynomial interpolation. Therefore, Figure 10 shows the calibration curve and the polynomial interpolation for OLF spring extensometer L1.

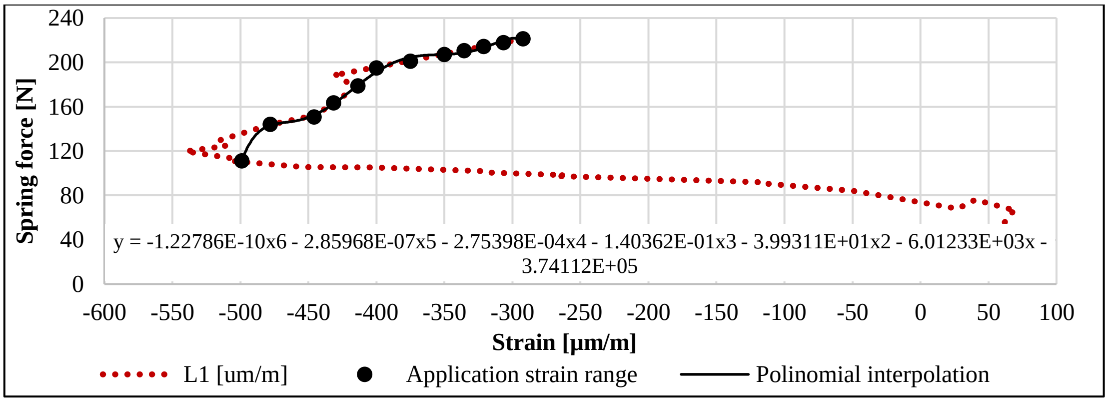


Figure 10. – Polynomial interpolation for OLF L1.

The polynomial curve, which is shown as a solid line, was used as an interpolation for the force calculation from the strain values. It is possible to notice that only a part of the original curve is being used, this is due to the application condition, wherefrom the installation position the spring can only be compressed.

Figure 11 shows an example of strain data collected, where the temperature compensation was already applied. Also, temperature values for the same run are shown.

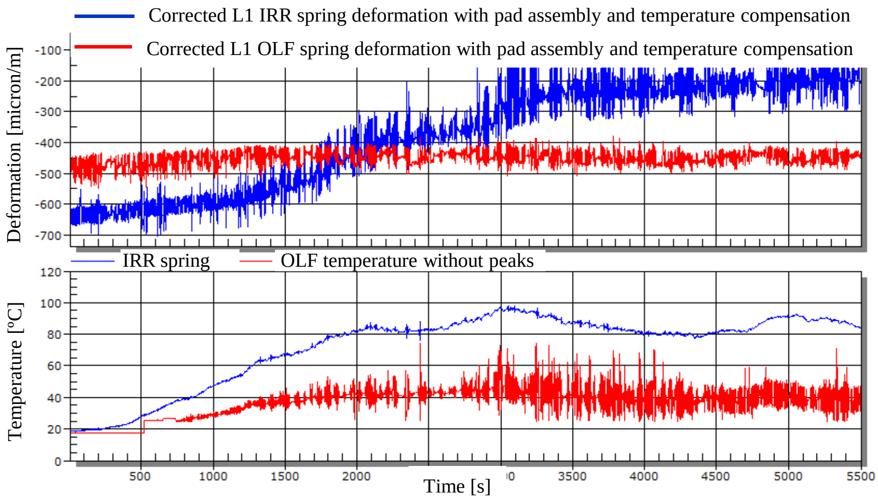


Figure 11. – Strain for springs OLF and IRR.

There is a noticeable difference between the strain profiles of OLF and IRR springs, according to Figure 11. OLF spring shows a uniform variation of strain, while IRR springs show a non-uniform variation, where the strain increases over time. The behavior of IRR springs is considered inconsistent, once the average strain should converge to the static installation position, which is constant over time. If temperature data is analyzed, it is possible to understand that IRR spring is exposed to higher temperatures, and the glue used to bond the extensometers on the springs is recommended for temperatures lower than 80 °C. Due to this problem, strain data collected on temperatures over the limit of the glue were disregarded.

Force values are shown directly in the next section, in a comparison with the force calculated using acceleration data.

3.3.3 Correlation between forces calculated through acceleration and strain

In order to verify whether the force calculation method from the acceleration data, represents the actual dynamic application loads for the springs, a comparison was made between these data and the force calculated by the extensometers, as shown in Figure 12. For this evaluation, data collected for run 1 of the OLF spring were considered, due to the temperatures being below 80 °C, as mentioned above.

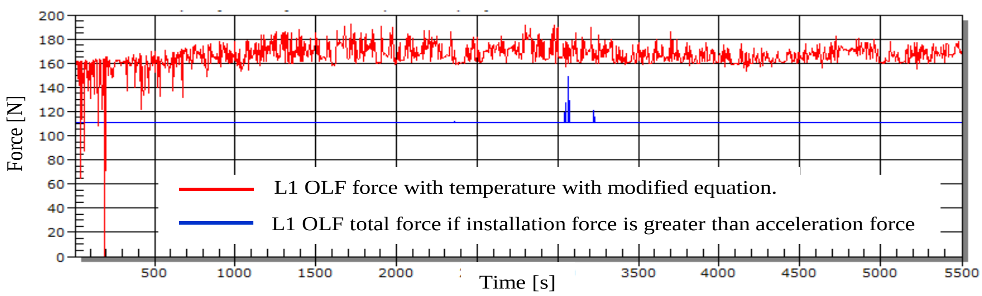


Figure 12. – Comparison of forces calculated using acceleration and strain data.

Values of force calculated through the acceleration of the vehicle axle showed the same behavior as values of force determined by strain interpolation, but always with a smaller magnitude. There were few occurrences where the force caused by the acceleration was greater than the spring installation force, and at these times, the extensometers had no sensitivity to identify fast fluctuation of small strain values, since this type of sensor is not intended for dynamic measurements – where accelerometers are used, for example –. According to these results, which were considered acceptable, it was necessary to evaluate the relative error between the two forms of calculation. The relative error showed a variation from 25% to 42%, where the average was 34%. Also, 92% of the run, showed errors around 35%.

This level of error can be considered acceptable, since these are analyses involving extensometers and temperature combined, where even with the compensation applied, errors inherent to this analysis are presented. The acceleration used is being measured on the vehicle axle, but there may be differences caused by mechanical amplification, component vibrations, and clearances in the connections. Extensometers are not recommended for strain measurements where small variations occur at very short periods, accelerometers are better suited for such applications.

4. CONCLUSIONS

This study allowed the understanding of the main loads to which a brake spring component is submitted, quantifying the requirements for the development of such component. Typically, the application of urban transportation is severe in terms of durability, but deceleration and pressure are low, resulting in relatively low working temperatures – predominantly between 100ºC and 250°C –. However, the temperature proved to be very sensitive to the driving style, since brake pad temperatures of up to 350ºC were reached when an aggressive driving style was used.

Springs are exposed to a less confined environment than brake pads, consequently, working temperatures are lower. Spring and brake pad temperature profiles follow the same behavior, but with a difference between 40ºC and 80°C, being sensitive to the same brake pad variations concerning the driving style, for example. The working temperature regime of the springs is between 50ºC and 150°C in usual conditions, but for more critical conditions it can reach up to 200°C.

Different application conditions were not evaluated, but the urban public transportation route is not very aggressive concerning the accelerations to which the vehicle is submitted, since, in general, the lanes are paved, thus, there are fewer imperfections on the road, resulting in lower vertical accelerations in the vehicle's suspension. In this study, the average acceleration values found were between 0.5g and 1.5g, reaching peak values of up to 8g in a few occurrences.

For this type of application, the installation spring force was around 110N and 130N, however, as the accelerations are relatively low, there are few events in which the installation force is exceeded, generating brake pad displacement. Springs need to maintain stiffness with increasing temperature, as the installation force needs to be the same at a working temperature of up to 200°C. The springs analyzed here have constant stiffness at temperatures of up to 180°C.

The proposed method for calculating force from Newton's Second Law has been validated by force interpolation through extensometers. Errors from the comparison between these two methods for calculating force are regarded to the several simplifications applied, thermal effects and to the high strain sensitivity of the measured points. The main reason that explains the differences is based on the extensometers, which showed not to be a good tool for this kind of application, where dynamic loads and temperatures over 100°C take place.

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