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Brake systems tribological analysis and their evolution in sustainable characterization

Análisis tribológico de sistemas de frenos y su evolución en la caracterización sustentable

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Abstract

This research aimed to analyze the different brake systems using tribology as a tool for the optimization of controlled systems. Automotive braking systems in high-tech technology were analyzed to identify the variables involved and relate them to the results of the different tribological studies. Traditional braking systems were compared with respect to the regenerative ones used in high-end hybrid and electric cars, in order to identify the technologies applied in tribological systems and their evolution. The variables analyzed were force, contact area, friction coefficient, force cyclical variation, rpm, time, acoustic emission, sliding speed, torque, temperature, and surface misalignment, among others. The results of the different case studies determined that regenerative brake systems are prototypes in continuous sustainable evolution and tribology, together with electronics, contributes with analyzes to achieve more precise controlled systems.

Sustainable braking technology, Tribological studies, Regenerative brake systems

Resumen

Esta investigación tuvo como objetivo analizar los diferentes sistemas de frenos utilizando como herramienta la tribología para la optimización de sistemas controlados. Sistemas de frenado en automóviles de alta vanguardia tecnológica fueron analizados para identificar las variables involucradas y relacionarlas con los resultados de los diferentes estudios tribológicos. Sistemas de frenado tradicionales fueron confrontados con respecto a los regenerativos utilizados en autos híbridos y eléctricos de alta gama, con la finalidad de identificar las tecnologías aplicadas en sistemas tribológicos y su evolución. Las variables analizadas fueron fuerza, área de contacto, coeficiente de fricción, variación cíclica de la fuerza, rpm, tiempo, emisión acústica, velocidad de deslizamiento, torque, temperatura, desalineación de la superficie entre otras. Los resultados de los diferentes casos de estudio determinaron que los sistemas de frenos regenerativos son prototipos en evolución continua sustentable y la tribología en conjunto con la electrónica contribuyen con análisis para lograr sistemas controlados de mayor precisión.

Tecnología de frenado sustentable, Estudios tribológicos, Sistemas de frenos regenerativos

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Introduction

Tribology analyzes the quantification of wear phenomena at the macro, micro, and nanoscale levels such as abrasion, adhesion, sliding, cracking, fatigue, rolling contact, delamination, cavitation, impact, corrosion, and erosion, or a combination of these. The metrology of the wear types in cyclic behaviors identifies the critical factors that will be standardized under ISO 25178 to understand, predict and control the problem. The primary objective of tribology is to optimize the design of a component or assembly to propose a surface finishing process, coating formulation, or lubrication method. (Lugt, 2016; Stoica & Tudor, 2015). The tribology objectives is to minimize wear, optimizing friction as a function of temperature in the contact area in brakes, clutches, and tires. (Benalcázar & Gabriela, 2022; Li et al., 2018; Syahir et al., 2017).

Braking is related to the wear phenomena due to abrasion, sliding, and adhesion, mainly causing an increase in temperature that is transmitted to the entire system, generating the transformation of energy between a fixed part "caliper" and a rotating "disc". When we activate the brake pedal, it is pressurized by a hydraulic circuit that moves the brake pads, exerting pressure on the disc until it locks. The pads must withstand high temperatures without excessive wear, but with a friction coefficient sufficient to achieve the braking conditions required in the vehicle by the user or by an automated system that help the vehicle detect objects that could potentially affect its trajectory. (Zhao et al., 2018)

The friction coefficient of the pad material must be as stable as possible at different speeds, pressures, and temperatures so that the driver or the automatic braking system can anticipate the vehicle's reaction to different operating or environmental conditions. (Benedetti et al., 2017; Fernandes, 2016). Braking systems were classified into; hydraulic and combined. The hydraulic systems can be divided into three groups; disc, drum, and hand. Combined braking systems were; hydraulic and electric – hydraulic. Combined electric-hydraulic systems were called “regenerative”.

The handbrake was only applied to the rear tires while in some cases the braking systems may be mixed on one mobile depending on the drive wheels number (directly connected to the transmission). In the case of regenerative braking systems, they can only be applied to systems directly coupled to the transmission. (Bauer, 2019; Fernandes, 2016)

Figure 1 Regenerative braking system
Source: Fernandes M. (2016)

Regenerative brakes are different from friction brakes, in that the electric motor works in reverse when the driver hits the brakes. The vehicle slows down and, at the same time, electricity was generated and stored in the battery for reuse. With traditional braking systems, this energy is lost in the form of heat, but in regenerative braking systems, the energy was used, improving the energy efficiency of the vehicle and extending the useful life of the braking system due to less wear. (Champi & Abel, 2022; Tormos et al., 2017)

In combined brake systems, the car's computer determines when to activate the friction or regenerative braking system. A slight reduction in force on the brake pedal causes the vehicle's electronics to activate the regenerative brakes and place the motor in reverse to generate electrical energy that will be sent to the battery bank. On the contrary, if the vehicle needs to stop quickly to avoid a collision, only the conventional brakes will be applied to avoid damaging the regenerative systems, which depend entirely on the programmed logic of activation and deactivation of the electronic systems in the event of a vehicle operation. The user that develops in an environment. (Gong et al., 2015; Ma & Zhan, 2015).

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These systems use many additional sensors to send signals to a central computer, which, under programmed logic, identifies in an algorithm the response that will be sent to the braking system according to the user's operating condition with its environment. The response of combined friction and regenerative braking system requires a feedback system in a closed-loop circuit. On the other hand, one of the drawbacks of these electronic systems are the environmental conditions, which can be unpredictable for the logical control system, such as snow, hydroplaning, pollutants, poor track conditions, and irregular soils such as dirt or roads in inappropriate conditions, among others, which, by not having the capacity to respond to adverse conditions, generates an arbitrary response within its possibilities that does not optimize the regenerative braking system. (Gong et al., 2015; Ma & Zhan, 2015).

Since we are talking about hybrid and electric vehicles, where efficiency is a priority, systems will always try to maximize the amount of braking torque provided by regeneration which is directly proportional to generator voltage feedback which was limited. by the speed at which the batteries can absorb energy and by the state of charge of the battery, (if it is fully charged it is not possible to store it. (Wicki & Erik, 2017)

The perfect brake pad in terms of friction performance, wear, noise, operating temperature, and costs have not been found to date, because the idealizations are: low speeds and pressures, decrease in settling time, and use of brake energy. dissipation friction, generation of maximum torque output, and no corrosion. (Mukoyama et al., 2017).

The closest modeling attempts are related to the generation of tribological banks, which base their designs on the analysis of experiments and the creation of feedback algorithms for the generation of software, where the choice of the system variables and their limit conditions allow a replica of real system scaling.

Obtaining high-precision data depends on the interfaces of the different sensing devices that deliver signal spectra that can be analyzed separately, but tribology establishes that as a critical point of analysis, the relationship between these to be interpreted and represent the scientific foundation in decision-making in engineering areas, to lay the foundations to generate new controlled technologies. (Kumar et al., 2018; Shababi et al., 2017)

The tribological properties during the braking phenomenon have an influence on the operation and its failures such as noise and vibrations that appear at very low sliding speeds for another phenomenon called sliding to occur, the static friction coefficient (μs) between two braking surfaces contact of the friction materials must be greater than the kinetic friction coefficient (μk). (Shababi et al., 2017 ; Zhang et al., 2016). The adhesion slip phenomenon generally appears at very low slip speeds as intermittence in the friction process caused by differences between the values of kinetic and static friction coefficients. This research analyzes the contributions of tribology in standard vs regenerative braking systems, showing the form of analysis based on test benches designed for the purpose to obtain controlled tests so that they can iterate these variables in electronic sensing models. to automate braking control systems in high-end electric cars.

Tribological analysis tests

Tribological tests of traditional friction braking systems, actuated by hydraulic systems, were analyzed by different authors, identifying the friction coefficient as a fundamental parameter based on the materials involved in the tests. (Shababi et al., 2017). All these study cases required control of different test variables such as force, contact area, friction coefficient, cyclical variation of force, rpm, time, acoustic emission, sliding speed, circular paths on the disk of contact, torque, temperature, surface misalignment, contacts, contaminated, dry and wet under different lubrication regimes among others.

The tests were carried out in different types of tribometers, both horizontal and vertical, with standardized tests that used the Pin on disc method under the ASTM G-99 standard. The objective of these tests was in all cases, to determine the behavior of different steel types in the manufacture of braking disc systems, as well as the proposal to use stainless steel to manufacture corrosion-free braking discs. On the other hand, the materials used in the manufacture of different brake pad types were used for the manufacture of bolts. These contacts were analyzed for their abrasive and adhesive wear behavior as a function of the variation of the aforementioned test variables to identify the optimization of test parameters in the different contact types, which optimized the coefficients of friction in the range of 0 – 3.

Most tests were carried out in the range of the following parameters: maximum sliding speed: 0.13 - 0.3 m/s, maximum contact pressure: 0.88 - 0.1 MPa, total sliding time: 2 - 300 s, disc mass : 0.167 - 0.3 g, specific heat for gray cast iron: 560 J / (kg K), angular speed 1 - 25 rad/s, normal load of (25, 50, 75, 100, 150, 200) N, speeds (20 , 40, 60, 80, 100) rpm, acoustic emission from 4 - 70 dB, braking contact temperature at different speeds; calculated at closed contact 100 - 1100 °C. (Huang et al. 2019; Nuñez & Andree, 2022; Shababi et al., 2017,)

The friction coefficient and the acoustic emission identified from several tests that when the load was increased the acoustic emission increased, in the last part of the tests in a cyclical way with only a few intermittences. For a better understanding of what was happening, they chose 10-s test periods to highlight the phenomenon. In these short-term tests, it was observed that the coefficient of friction and the acoustic emission between seconds 200 and 210 of the 300-s test, the disc makes a complete rotation every second, and the coefficient of friction presented the same evolution from one cycle to another. Therefore, it was decided to reduce the period to 2 s with the same test conditions, identifying that compared to the tests in which we do not have acoustic emission, there is a drop and sudden increases in the values of the coefficient of friction that was repeated every cycle with different amplitudes that were considered a slip period. (Kumar et al., 2018).

During this period just before the contact block, it was possible to identify that most of the energy is lost during stop-and-go driving, which is the energy absorption optimization period that we are looking for so that the regenerative brakes are more efficient. During the braking tests, it was identified that up to 80% of the energy could be lost in the stopping and starting phenomena where the temperature was measured by conduction because it is the method of greater precision and accuracy with economic instrumentation. Previous case studies have identified that regenerative braking can often retain nearly half of that lost energy that was converted to heat by closing the ignition. This energy can be transformed by regenerative systems into electrical energy that will help, in the case of hybrid cars, in greater efficiency of fossil fuel, helping to conserve the environment with a sustainable development system.

The identification of energy loss of friction braking systems in pin-on-disc tests determined that, if we use a regenerative braking system at this critical point, these two systems work better together. Regenerative brakes reduce energy loss, but they are not designed to be the only braking system on a vehicle. Their effectiveness was limited at low speeds, and they simply cannot stop a vehicle suddenly. They also cannot be used as a parking brake to prevent a parked car from rolling downhill. (Das et al., 2017). Finally, two-wheel drive vehicles do not have four-wheel drive motors; therefore regenerative braking cannot be used on the other two wheels of the vehicle.

Working together, traditional or friction brakes provide the safety factor of allowing sudden stops, while regenerative brakes reduce the temperature, pressure, and the number of times friction brakes must be used. (Ishizaka et al., 2017; Zhang et al., 2016). As vehicles fitted with regenerative brakes use friction brakes less frequently, brake dust and emissions will be reduced, but the build-up of a uniformly transferred layer of wear particles, necessary to achieve full torque in the engine, will be reduced, and total or partial braking moment. (Kumar et al., 2018)

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Pin on disc tribological tests for hydraulic braking systems in a frictional contact in controlled media with the presence of a third body in the contact such as a contaminant or wet condition has been exceeded to test regenerative braking systems. This test requires modifications to conform to the new combined friction and regenerative brake standards (under SAE J2789, SAE J2707, SAE J2784, SAE J2923, SAE J2522, and SAE J2521). The tests require adjustments to include tests at lower temperatures and different braking profiles. The new dynamometers must be able to reproduce the combined effects of both braking systems at the same time with the generation of spectrum signals in real-time.

However, full-scale dynamometer testing is expensive, time-consuming, and highly trained staff involved in research to interpret the output data that will be used by peers in other disciplines to program electronic systems to investigate the optimization of the combined system to be able to propose a profitable automotive patent that allows mass production and cheaper technologies such as friction brakes. At present, countries with great technological developments have generated, together with their most specialized Technologists, machines that propose solutions to modern industry and that, in a perfect balance between Applied Research - Industry - Government, develop test benches that revolutionize technology.

Nowadays, Countries with great technological developments have generated, together with their most specialized Technologists, machines that propose solutions to modern industry and that, in a perfect balance between Applied Research - Industry - Government, develop test benches that revolutionize technology. The Model M3000 Brake Dynamometer allows testing of conventional, electro-hydraulic, electro-mechanical, regenerative hybrid-hydraulic systems. It is equipped with a DC drive motor, which allows a wide range of rotational speeds to be reached up to 2500 rpm, allowing a wide range of vehicles to be tested up to their maximum speed, in some cases 350 km/h., even plus. The M3000 allows the dynamic inertia simulation in the range of 5 kgm^2 to 250 kgm^2.

This means that we can test a wide range of vehicles, from light passenger cars, and heavy SUVs, to light commercial vehicles. This can break with a braking torque of up to 5650 N-m, which allows doing 10 m/s^2 for all the mentioned vehicles and much more for some lighter ones. See figure 02.

The station data acquisition of the M3000 allows to record in real-time on the timeline the following signals: braking torque, rotational speed, linear speed, deceleration, mechanical vibrations, dynamic unbalance, relative and absolute humidity, pad temperature, disc temperature, drum temperature, generator temperature, brake pressure, acceleration, fluid displacement, actual inertia, cooling the air temperature, cooling airflow high-speed camera image, thickness variation of the disk, peak noise level, peak noise frequency, peak noise duration, data acquisition and analysis, all signals can be recorded in real-time and on the timeline, signals can be stored with frequency up to 1000 Hz, free online technical support to analyze the results and compare them with the data obtained in other friction material.

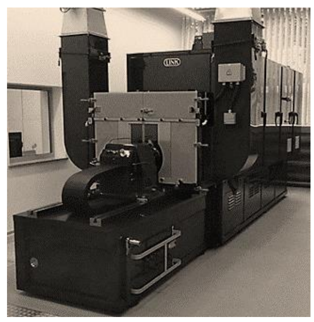

Figure 2 M3000 Brake Dynamometer for brake testing
Source: BOSMAL Automotive Research and Development Institute Ltd (2022)

Making the test procedure easier is possible on a small scale using M3000 tribometers. This saves time, and financial resources, and enables early sorting of materials, without the need for large-scale component evaluation. (Huang et al., 2017; Ishizaka et al., 2017). Another advantage of this approach is the ability to precisely control critical parameters on an internationally certified machine. (Campuzano-García et al., 2022; Soto & Montañez, 2022).

Results discussion

Hydraulic friction brakes have many recommendations in favor. They are a very effective means of providing the large amounts of braking torque needed to stop a vehicle. They are also relatively cheap and generally very reliable. However, because they depend on the act of pressing a friction material against a moving surface, the physical characteristics intelligently change over time by the rheological conditions of the compression fluid, depending on the user's driving conditions. the environment and unpredictable media, although they do not regenerate the heat energy produced by them, they are currently used as a means of braking in hybrid-electric cars due to their simplicity, economy, and responsiveness, complying with GNC systems. (Good, Nice, and Cheap), which is not that they are of poor quality, because the theories indicate that high-quality systems are expensive for having gone through a whole testing process, however, these systems have passed all those quality tests for decades and have passed them. These hydraulic braking systems are one step ahead of where the technology has been transferred and made cheaper by mass production in the automotive industry.

The contaminants layers in the contact reduce the frictional forces and increase slippage, but as the contact passes, a contaminant expulsion sweep was generated, recovering the real area of contact and adhesion with a laminar layer of wear particles that standardize: temperature transmission by conduction to the brake pad and the friction coefficient in the entire contact area.

An increase in the hydraulic pressure of the contact braking systems increases the acoustic emission, but if a third body appears in the contact, the acoustic emissions are tripled due to the slippage that it presents in the contact and the friction coefficient decreases.

It was considered that 80% of the heat generated by friction in the disc was dissipated through the phenomena of heat transfer by conduction, convection, and radiation. If this braking energy converted into heat energy is stopped so that it is not converted into heat but into rotational energy in the opposite direction to that of the braking disc, it can produce a torque in a synchronous generator system that, when the turns are cut, can supply electrical energy. On the other hand, the friction braking system will not heat up, because the regenerative system will slow down the rotation and the disc brake pad friction system now become auxiliary or emergency in case of sudden braking or at low speeds where the regenerative braking system did not reach its activation.

Regenerative braking systems currently represent a technological challenge that until now is under development and is only used in test prototypes for idealistic conditions with established parameters such as infrastructure and racing cars. These test conditions have simplified the reaction algorithm of the electronic systems that activate and deactivate the regenerative braking system. (delimitation of the study problem).

The proposal of advanced tribological machinery is a reality, but also high-cost specialized machinery with a whole set of physical infrastructure requirements, of specialized personnel to be able to operate them and exploit a whole set of technological contributions to the automotive sector. These systems may represent a set of capitalization opportunities when a good business vision is combined, a business plan for a Department of Technological Development specialized in braking systems of the private industry, the Automotive Industry, or for a Technological Development Center University that through its laboratories comply with the certifications that demonstrate its competence of services under international standards ISO 9001 and/or that its results are valid and repeatable (international accreditation ISO 17025), IEC 17025: 2017 or its Mexican equivalent, the NMX-EC-17025-IMNC-2018 standard, EMA (Mexican accreditation entity, A.C.), together with the Good Laboratory Practices (GLP) of the Organization for Economic Cooperation and Development (OECD).

But for an Engineering Educational Center this type of equipment in its laboratory represents an unattainable investment for many and in addition to lacking laboratory certifications that allow services to be sold to the business sector and are little used to carry out laboratory practices of related subjects, for what is recommended for these last Centers, the manufacture of their machinery based on the knowledge of the technologies developed in first world countries or the purchase of essential branded pin on disc equipment for pedagogical purposes so that engineering students can understand how: do they work. Once engineering students can understand how specialized equipment is tested or developed, they will need to continue to specialize so that when they come into contact with a specialized team of this magnitude they can develop patent-worthy contribution technologies among their peers. Without forgetting that the technological advance in this equipment is by leaps and bounds, the high technology centers with certified laboratories will have around 3 to 5 years to exploit them technologically, after this time it represents test equipment that for the world of research and technological development is obsolete. But it may be enabled for teaching.

Conclusions

Tribological improvements in automotive systems generate energy savings of around 18.6%. As with traditional brakes, tribology and friction reduction play an important role in regenerative brakes. Future engineering and current research aim to combine friction and regenerative brakes to minimize energy loss and maximize effectiveness. As regenerative brakes continue to evolve, friction brakes may one day become obsolete. SAE is developing tests that measure the combined performance of traditional and regenerative brakes under SAE J2789, SAE J2707, SAE J2784, SAE J2923, SAE J2522, and SAE J2521 standards.

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