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DEVELOPMENT OF A MULTIDISCIPLINARY METHODOLOGY FOR BRAKE DISC DESIGN

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Abstract

This paper shows the methodology used in the development of brake rotor, from the geometry design until the realization of functional tests and validations, relating several disciplines.

The brake disc development needs multidisciplinar work equipment. It is necessary a deep knowledge in disciplines as different as Mechanics, Thermodynamics, Metallurgy, Tooling, Acoustics and Vibrations, Electronics, etc.

To carry out the proposed methodology it is necessary use a wide number of software to simulate different physical phenomenon, as well as a big number of validation and test equipment.

Resumen

Este artículo muestra la metodología empleada para el desarrollo de discos de freno, desde el diseño de la geometría hasta la realización de ensayos funcionales y de validación, relacionando entre sí distintas disciplinas.

El desarrollo de discos de freno necesita de un grupo multidisciplinar de trabajo, el cual debe tener necesariamente un profundo conocimiento en disciplinas tan diferentes como Mecánica, Termodinámica, Metalotecnia, Fabricación, Acústica y Vibraciones, Electrónica, etc.

Para poder llevar a cabo lo propuesto en esta metodología de trabajo, se debe contar con un importante número de programas de simulación de diversos campos así como un gran número de medios de ensayo y validación.

Keywords: Brake Disc Design, Multidisciplinary Methodology, Simulation, Testing, Validation.

1. Introduction

For suppliers in the automotive industry, to participate in the parts or components design means to be able to give judgement and improvements in the pieces design, improving the products, simplifying the manufacture and reducing its cost.

On the other hand, most of the component suppliers must improve the services that offer to their customers, to reach a high competitiveness level, to overcome their competitors, as much in a regional or national as in an international context.

The requirements are very severe for safety components suppliers that design and develop their own components. This is the case of the design of braking system components.

During the brake disc design, it is necessary to consider different subjects (geometry, weight, material, maximum work temperature, crack resistance, thermal distortions, casting, noise, etc…). All this subjects must be included in an appropriate design methodology

Automotive brakes have to fulfil a complex set of requirements, with safety being the most important. The brakes have to work safely and predictably during all circumstances, which calls for a stable friction level regardless of temperature and environmental factors.

This document is focused on showing the different technical disciplines that must be taken into account in the brake disc design, and how the interrelation among them is.

The friction brakes are required to transform large amounts of kinetic energy into heat at the contact surfaces between the disc and the pad. The rotor absorbs this energy by means of conduction, which must be dissipated quickly by means of conduction and convection to the ambient surrounding air. When the temperature increases to a higher degree, radiation also helps to dissipate the energy from the heated rotor.

The Kinetic Energy that a brake disc absorbs during a brake application, satisfies the next mathematical equation:

$$E_{kin,brake\_disc} = K \cdot \frac{1}{2} \cdot \gamma \cdot \frac{m \cdot (v_o - v_f)^2}{2} , \qquad (1)$$

where m is the vehicle mass, in kg.

γ is the axle weight distribution coefficient ($0 \leq \gamma \leq 1$).

v_o is the initial vehicle speed, in m/s.

v_f is the vehicle speed at the end of the braking application, in m/s, and

K is the porcentage of kinetic energy that the disc absorbs, approximately 0,90 (90%). The rest goes to the pads.

Part of this energy is stored as heat in the disc. The rest of energy is dissipated by conduction, convection and radiation, according to this expression:

$$Q = C_p \cdot m_{disc} \cdot \Delta T + Q_{convection} + Q_{radiation} + Q_{conduction} \qquad (2)$$

where Q is the thermal input energy from the kinetic energy (J),

C_p is the specific heat of the GCI (J/kg K),

m_{disc} is the disc weight (kg),

ΔT, is the temperature increase in the disc from the initial state (K).

$Q_{convection}$ is the part of heat dissipated by convection (J)

$Q_{radiation}$ is the part of heat dissipated by radiation (J), and

$Q_{conduction}$ is the part of heat dissipated by conduction (J), to the rest of brake elements.

It is very desirable to be able to analyse alternative designs and materials at the pre-prototype stage by developing computer models of the brake thermal performance and structural integrity.

However, any new design of brake rotor must be validated by on-dyno or on-vehicle testing. Both ways of study, simulation and experimentation, must be presented in an appropriate brake disc design methodology.

Other interesting aspect is to know how the disc casting process previously to the mould tool kit construction will be. With this study is possible to avoid problems during the casting of the new disc design.

So, this technical paper tries to show the multidisciplinary methodology for brake disc design developed in the Fundación CIDAUT, by the Active Safety Area, which considers all the different subjects seen above.

2. Methodology

With the developed methodology it is possible to tackle the two more common necessities. On one hand, the whole development of a brake disc, from its conception until its launch into market. On the other hand, this methodology could solve isolated problems in a particular disc model. This problem could appear in any stage of the methodology. During this description, a whole brake disc development is explained.

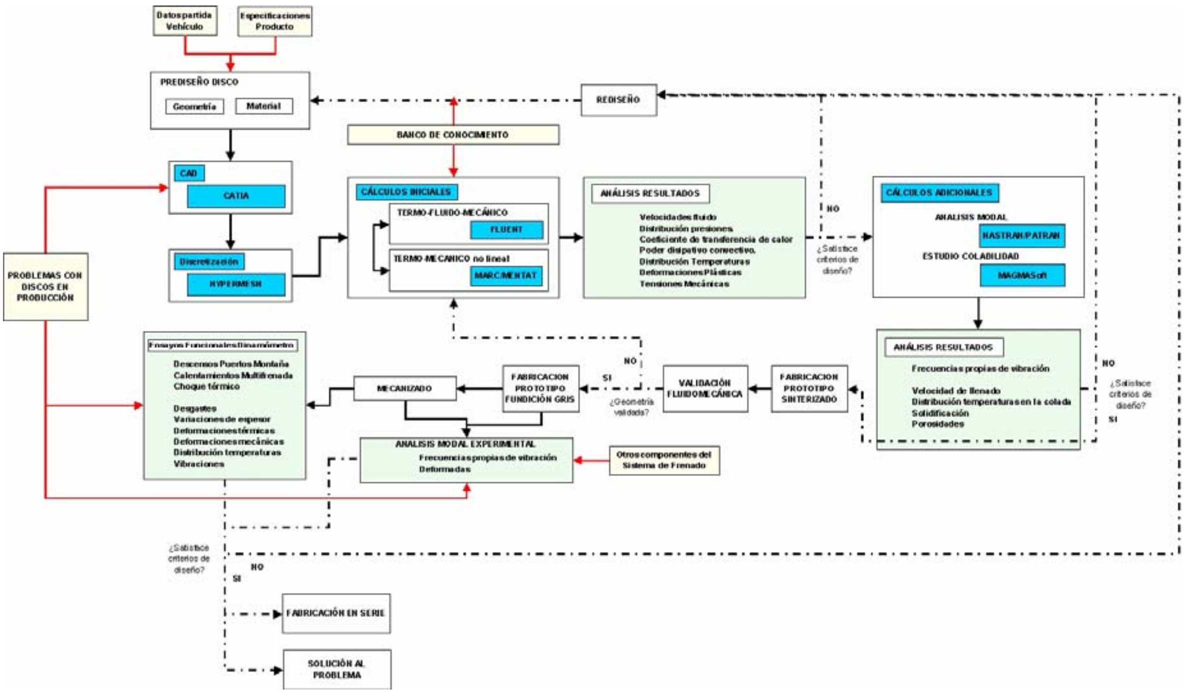

Figure 1. Disc Design Methodology Flow Diagram Developed by CIDAUT

2.1 Know How Basis

Through a long learning process, a know-how base has been created, which is a very important piece into the design methodology. This part of the design methodology is made up by knowledge in Materials, CAE Simulation and Testing.

Materials

Knowledge of the physical properties, as much thermal as mechanic, is a very important point in the brake disc design. The working temperature range in the brake disc is very wide, reaching temperatures in some cases in the order of 800º C. For this reason, to know the properties variation against the temperature is a very important information.

Properties as thermal conductivity, specific heat, thermal expansion, tensile strength (Fig. 2), etc, change significantly its values with the temperature. This behaviour of the GCI, even the air properties variations, must be properly implemented in the simulation software.

CAE Simulation

To have a deep knowledge about the problem to solve with the software, helps quite a lot. At the moment, an unique software able to resolve the fluid-dynamics and the non-linear thermo-mechanical problems does not exist. This makes that the methodology must use different software programs in each case, and must develop tools to transfer the output data from the fluid-dynamics solutions to the thermo-mechanical simulation.

Testing

During the methodology setup, the results correlation between simulation and experimentation is very import. In this stage, it is necessary to count on the appropriate equipments to be able to measure the control variables defined in the simulations. But the right use and the correct interpretation of the measurements are more important than the equipment. In some case it could be interesting to develop support tools to make easier the data processing and its analysis.

2.2 Input Data

As starting point, it is necessary to know some technical data of the vehicle where the disc will be assembled (gross vehicle mass, axle weight distributions, Max speed, loaded tire dynamics radius, etc…).

Additionally, it is advisable to have product specifications from the customer, where it is possible to find other important information about chemical composition, max disc weight, mechanical characteristics, machining, etc.

From the customer it is very interesting also to collect different testing procedures, to know which kind of functional test must satisfy the final product (heating, cooling, alpine descent, thermal cracks, wear, residual drag, etc.).

2.3 Pre-design

With the input data and the experience of the work group, some pre-design will be proposed, chosing the more appropriate geometries and material compositions, accordingly to the vehicle which will use the disc.

During this stage, the general disc geometry (back-vented or front-vented) and the fin geometry in vented disc (straight, curved or pillar-typed fin) are chosen.

In brake rotor design, fin configuration is altered to maximise airflow for effective heat removal during braking.

With respect to the material composition, although the methodology allows to use Aluminium Metal Matrix Composites (Al MMC), or even Carbon/Carbon, Gray Cast Iron Discs (GCI Discs) are actually the main demand. During this pre-design stage is necessary to select what kind of GCI is the best option, according to the input data. Actually, the use of High Carbon content is common, because of the good thermo-mechanic characteristics, although it is possible to use Medium Carbon Content.

2.4 Mesh generation

The meshing is a very critical phase into the methodology. The simulation results quality in the simulations depends on the mesh. Each simulation (CFD or FEA) needs a special way of meshing, fact that forces us to use two different mesh conditions, to be carried out with two differents software. The used mesh kind is the more appropriate in each case.

2.5 Computational Fluid Dynamics Simulation (CFD)

In the CFD analysis the airflow through the brake rotor is assumed to be steady, incompressible and turbulent according to a k-ε turbulence model.

The convection phenomenon is expressed by this equation:

$$\dot{q}_{convection} = h \cdot A_{disc} \cdot \left(T_{disc} - T_{air}\right) \tag{3}$$

where $\dot{q}_{convection}$ is the convection heat flow (W),

h is the heat transfer coefficient (W/m^2K),

A_{disc} is the free brake disc surface (m^2),

T_{disc} is the disc temperature (K), and

T_{air} is the surrounding air temperature (K).

After several investigations, it is correct to accept that the heat transfer coefficient ("h") is only dependent on the airflow. In a transient heating, where the disc is rotating at a constant speed, the rotor temperature does not modify significantly the "h" values.

As the rotor temperature could reach values higher than 400º C, the heat loss by radiation is not neglected. The radiation phenomenon is expressed by this equation:

$$\dot{q}_{radiation} = \varepsilon \cdot \sigma \cdot A_{disc} \cdot \left(T_{disc}^4 - T_{\infty}^4\right) \tag{4}$$

where $\dot{q}_{radiation}$ is the radiation heat flow (W),

ε is the infrared emisitivity of the brake disc,

σ is the Stefan-Boltzmann constant (W/m^2K)

A_{disc} is the free brake disc surface (m^2),

T_{disc} is the disc temperature (K), and

T_{∞} is the environmental air temperature (K).

Brake cooling is an important target in the automotive industry. The brake optimisation is a essential criterion to improve the brake system efficiency. The final aim of a brake cooling optimisation is to get higher convective heat transfer coefficient on the disc surface and to increase the brake thermal power transferred to the cooling air.

The cooling efficiency mainly depends on the mass flow rate through the inner channels and the average convective heat transfer coefficient on the channels surfaces. The values of these two parameters, together with the air velocity components, allow us to know the flow behaviour for every studied geometry.

At the end of this stage, the local heat transfer coefficient over the surface of the CFD model will be known for each geometry, at different rotation speeds. This data will be the input for the following thermo-mechanical study.

2.6 Thermo-mechanical analysis

The purpose of this analysis is to predict the temperatures and corresponding thermal stresses in the brake disc. As in the CFD analysis, only one fin is considered, due to geometrical symmetry.

As an assumption for this analysis, the frictional heat generated by brake pads is distributed uniformly over the whole exterior area of the disc plates. This heat input flow ($\dot{Q}$), is calculated from the rotation speed and the friction force, for a particular testing conditions.

In an inertial brake application (deceleration), the instant input heat (W/m^2) is calculated using the following expression. In this case, the value of $\dot{Q}_{input}$ is variable in the time.

$$\dot{Q}_{input} = C \cdot \Omega = I \cdot \alpha \cdot \Omega \tag{5}$$

where $\dot{Q}_{input}$ is the instant input heat (W/m^2),

C is the braking torque (Nm)

Ω is the rotation speed (rad/s),

I is the inertia to stop by the brake disc (Kg m^2), and

α is the angular deceleration (rad/s^2).

In a non inertial brake application (constant speed, without deceleration), the heat input flow ($\dot{Q}$), is calculated with the following expression. In this other case, the value of $\dot{Q}_{input}$ is constant.

$$\dot{Q}_{input} = C \cdot \Omega = F_{\mu} \cdot R_{eq} \cdot \Omega \tag{6}$$

where $\dot{Q}_{input}$ is the instant input heat (W/m^2),

C is the braking torque (Nm)

F_{μ} is the braking force applied in the disc-pads interface (N),

R_{eq} is the equivalent brake radius where F_{μ} is applied (m), and

Ω is the rotation speed (rad/s).

In the methodology, the thermo-mechanical simulations fulfil the testing conditions accordingly to the test procedure collect in the Know How base.

The heat transfer coefficient calculated ("h") in the previous step (CFD analysis) will be used as thermal boundary conditions.

Heat loss from the model during braking and the following cooling periods occurs by convection and radiation from the free surfaces. The convection in the FEA model has been imposed by the FLUENT results. The radiation must be imposed in MARC using the provided radiation model.

In MARC the thermo-mechanical analysis is carried out in a coupled way. For each temporary step, MARC calculates the thermal and the mechanical fields.

In a brake disc, thermal deformations and stresses are caused by the non uniform thermal expansion and the mechanical boundary conditions. From the predicted non uniform temperature distributions, a non linear stress analysis is carried out for each time step of the thermal analysis, estimating the magnitude and direction of the thermal stresses.

In the brake design the best dimensional stability must be guarantied, trying to decrease the piston travel during the brake application and the non uniform disc wear. A smaller coning means a lower brake torque variation and a lower risk of suffering problems with the hot judder.

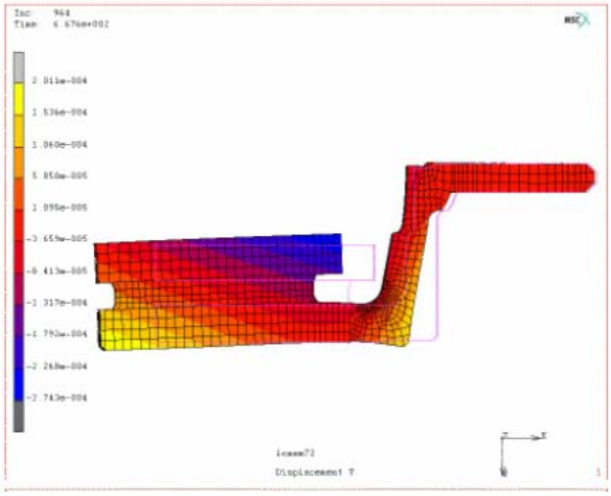

Figure 2. Thermal Distortion as result of a coupled thermo-mechanical simulation.

2.7 Analytic Modal Analysis

During the brake application, a small part of the kinetic energy is transferred into vibration energy. When the brake system has some of the mechanisms to accumulate vibration energy to certain level, squeal is created.

This disc brake noise is generally associated with the friction between pad and disc. The modes of vibration and natural frequencies have been associated generally with noise frequencies and there is strong evidence that suggests the brake noise frequency is related to a specific natural frequency and mode of the disc.

An unstable and large vibrating brake system has various means that facilitates mode coupling to transfer and accumulate vibration energy in addition of having several excitation mechanisms.

In order to avoid the mode coupling, it is possible to shift the vibrations frequency modifying the geometry, the number of fins or the material composition during the disc design phase.

In the methodology proposed, it is possible to use the FEA simulation to know the changes in the natural frequencies and the associated modal shape, against changes in the Young Module (composition), the disc geometry, the fin number and geometry, etc…

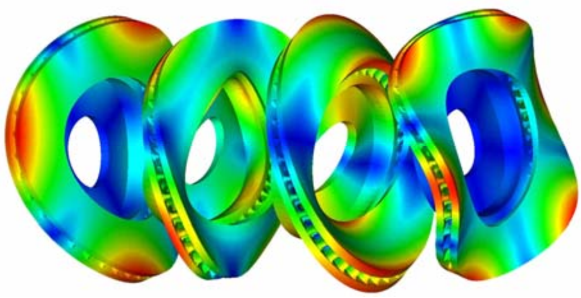

Figure 3. Out of Plane Modes in a Modal Analysis.

2.8 Fluid-Dynamic Validation

The more important thing in the design validation, as in the brake disc operation, is the cooling process. For this reason, the first step in the validation of the new disc models is to check the fluid-dynamic behaviour.

In this methodology stage, it is possible to compare the CFD results for a particular model, against the experimental ones. As the CFD results are very important in the proposed methodology, because they are the main base in the disc design, is highly advisable to check that the new geometry has the expected response before to manufacture it in GCI.

2.9 Casting Simulation

Once the proposed disc is selected, the next step is to check its casting process. Using MAGMASOFT, a software for casting process optimisation, the methodology has a good tool to know how the casting will be. MAGMASOFT provide a better understanding of mould filling, solidification, mechanical properties, thermal stresses and distortions, and minimising production risk.

For one disc geometry, it is possible to design the casting toolkits to obtain a process with a right velocity of filling, with absence of flaws and with an appropriate solidification rate.

2.10 Casting and tooling of the New GCI brake disc

After checking that the new disc model could be manufactured without problems, the next step is to melt the proposed geometry or geometries.

This phase is developed in the major share by our customer, Lingotes Especiales, a foundry what supplies brake rotor to the main European car manufacturers (PSA, General Motor, RENAULT, FORD, VW, etc). This company has a wide experience in the casting and tooling of brake rotor. This is a complicated phase. Only experienced mould makers are able to carry out it.

The casting process is very important for the later disc behaviour. Some aspects as casting variables, cooling speeds, inoculant content or GCI microstructure have a very important influence on hardness, wear, waviness, judder, thermal cracks, etc

The final machining influences on the Lateral Run-Out, Disc Thickness Variation (DTV) and Waviness. The numerical value of these machining defects must be controlled to avoid problem in the future, such as hot and cold judder, non uniform wear, vibrations, etc.

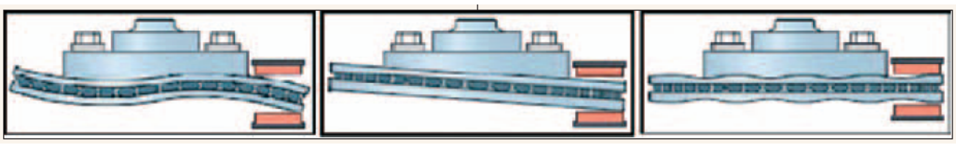

Figure 4. Waviness, Run Out and DTV on a brake disc.

2.11 Functional Test on Dynamometer

To carry out one functional test set is compulsory for the disc development. These tests must be chosen looking for diversity, that is to test the disc in different conditions trying to reproduce different running conditions (alpine test, highway brake application, fading test, thermal crack condition, disc wear resistance, residual drag, etc…)

Most of these test procedures are developed for testing on brake dynamometer. This special bench is a very useful tool to study the brake disc performance in different testing conditions. Test on dyno is an alternative option to do test on road with vehicle.

2.12 Thermal Validation

Different kinds of validations were carried out during the development of the methodology. The main validation was to check that the thermal results are the same as much from the simulations as from the experimental test on dyno.

In the thermal validation, the temperature evolution is analysed during the chosen brake test. In our case, the temperature in a point inside the disc brake plate is recorded, as much in the dynamometer as in the simulation. In any case, the measure point position is the same. This point is in the centre friction radius, in the middle of the brake plate thickness.

In an initial step, a validation was carried out according to a simple test, heating the disc at constant rotational speed. To reach these results, some model parameters were adjusted to achieve a good solution.

Showing the result of this kind of test, the temperature variation value between the experimental test and the FEA simulation is lower than ***2%*** during practically all the tests. Also, this narrow deviation is recorded in a wide temperature range (from 50º C until beyond 700º C).

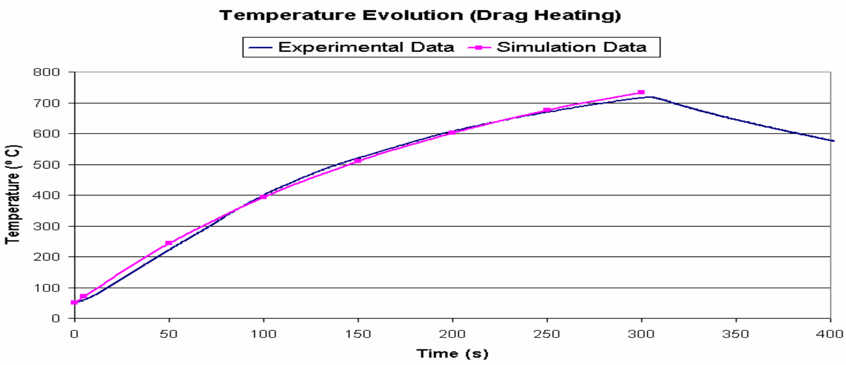

Figure 5. Drag Heating Test Simulation, by means of FEA and Dyno.

With this model, a new test was simulated, a multibrake heating. In this kind of test, the rotation speed is variable. This makes that the FEA analysis were more complex. Even so, the final result was completely satisfactory. The deviation is negligible, where its value is lower than ***1%.***

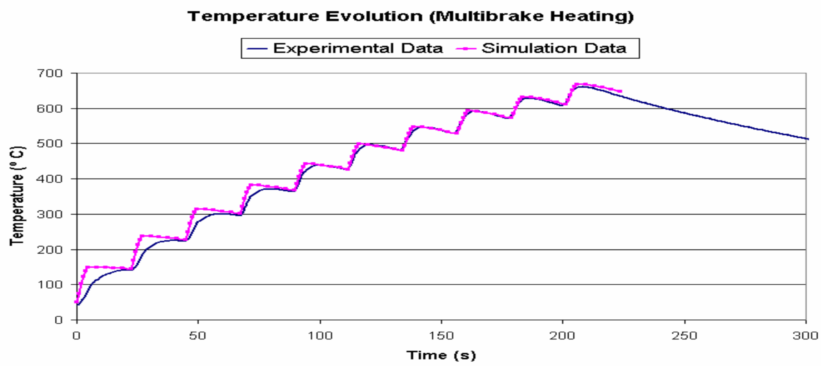

Figure 6. Multibrake Heating Test Simulation, by means of FEA and Dyno.

3. Conclusions

This paper shows the different tasks that have been considered in a brake disc design and development, collected in a work methodology. To miss out just an apparently negligible step in the proposed methodology, could make that the designed brake disc do not satisfy any specifications from the customer, turning the product into useless.

With this article, the authors also try to show the necessity of incorporate a large quantity of different disciplines in the design and development of brake discs.

For the studied disc geometry, the combined analysis with CFD and FEM software gives good results against the testing on dynamometer. The temperature deviation between both brake disc heating simulations is very small. The deviation can be evaluated around a 1,5% of the temperature value. This trend is registered in a wide temperature range.

These results can be reached independently of GCI composition, geometry disc, geometry fin, kind of test, etc, because of the strength of the design methodology.

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