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A practical solution to full circle brake pad actuation

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ABSTRACT

Although disc brakes have become the predominant automotive brake due to superior torque and fade resisting properties, conventional caliper brakes still leave room for improvement in important areas. These can be addressed by the use of full circle brake pads, which offer uniform dissipation of heat and distribution of engagement pressure, improved pad and rotor life, solutions to NVH issues and opportunities for enhanced performance and cost savings.

Advancing full circle pads into uniform rotor contact reliably and economically have been the design challenges. A variety of load application methods have been developed over the years yet adoption by the automotive industry has been prevented by technical or cost penalties associated with the methods of applying clamping force developed thus far. This paper reviews the performance and effectiveness of disc brakes employing full circle brake pads and demonstrates the utility of a helical mechanism to uniformly advance the brake pads and amplify actuation.

INTRODUCTION

The purpose of this paper is to demonstrate that a) the performance of disc brakes is improved by employing full circle (annular) brake pads, and b) a helically guided brake pad engagement mechanism is a superior method of advancing full circle pads into rotor contact, providing uniform engagement pressure and amplified actuation force.

Disc brakes have become the predominant automotive braking mechanism due to their superior brake torque and fade resistant properties when compared to braking methods employed since the early days of the automobile, most commonly drum brakes. Nevertheless, many brake engineers agree that conventional caliper disc brakes leave room for improvements in the following areas:

NVH ISSUES:

Noise, vibration and harshness are complex issues that involve the entire system of components from the brake itself through the wheel corner and are often most evident to the user through their interaction with the steering, brake pedal, and other interior features. Ongoing investigations in the industry have identified several initiating factors relating to the brake elements themselves which can be grouped into the following sections:

1. Brake disc hot spots which typically result in thermal judder.
2. Uneven rotor wear and rotor thickness variation.
3. Rotor defection and oscillation.

Additional NVH analysis relates to non-brake components such as the hydraulics, suspension elements, and so forth; however, this paper addresses features and functions strictly related to the brake structure itself.

THERMAL MANAGEMENT ISSUES:

1. Uneven heating of brake rotors can temporarily cause, or increase, thickness variation, and sometimes can produce a primary thermal buckling that warps the rotor into a washboard with three (sometimes five) high spots per revolution [1], [2].

2. Uneven rotor cooling in the case of a vehicle parked immediately following strenuous braking activity can cause the area of rotor under the brake pads to cool more slowly than the portion of the rotor open to the atmosphere, resulting in uneven thermal stresses in the rotor and leading to pad imprinting, residual internal stresses, and potentially catastrophic material failure.

PAD LIFE AND WEAR ISSUES:

1. It is well understood that pad life is a direct function of pad volume. For a given pad arc angle and

material wear characteristic increased wear life requires proportionally more pad volume and therefore increased pad thickness, which requires wider calipers. Increasing the pad arc angle requires longer calipers and usually additional pistons to achieve uniform loading over the longer pad.

2. Conventional brake pads are prone to longitudinal taper [3]. Non-uniform pad loading can result in taper wear at the leading and trailing edges of the linings.

PERFORMANCE LIMITATIONS RELATED TO SIZE AND PACKAGING CONSTRAINTS:

As vehicles become heavier and safety requirements more stringent, disc brakes will be required to provide yet greater stopping capability. With the existing format of calipers this typically leads to some combination of larger or additional pistons, bigger rotors, more aggressive pad materials, larger master cylinders and higher assist pressures. Each of these solutions carry penalties of cost, complexity, size and weight resulting from the need for larger and stronger components.

FULL CIRCLE PAD RATIONALE

ADVANTAGES & BENEFITS OF FULL CIRCLE PADS:

Conventional hydraulic disc brake caliper performance is a direct result of the applied force from the pistons. When additional force is needed for improved brake torque the common solutions are to increase the area of the pistons, requiring increased radial length of the pads and rotor, or additional pistons which results in a longer pad arc. Due to wheel and hub size constraints the typical approach is usually the latter. Extreme performance requirements such as those found in aircraft commonly utilize full circle pads.

A number of brake manufacturers such as Continental Teves and AP Racing now offer wider arc multiple piston calipers which necessitate an enlarged pad contact area. The full circle brake pad, however, maximizes the friction contact area, and can provide practical solutions to the issues presented above, as follows:

<u>NVH Solutions:</u>

1. Brake disc hot spots and resultant thermal judder – variations in the thermal distribution of friction created energy are minimized due to continual contact between the brake rotor and pad. Further minimizing effects occur due to partial heat transfer to the caliper housing via the pad itself, thereby reducing the total amount of energy being dispersed into the rotor.

2. Rotor wear and thickness variation - rotor high spots are in constant contact with the pad during braking. The constant contact avoids the phenomenon of a singularity event of a thick or thin zone on the rotor encountering and then exiting the pad zone. When the singularity events are eliminated, the reactive torque from the caliper structure is avoided which leads to minimal excitation or pulsation transmitted into the brake support structure. Continual contact of the rotor also creates a bridging effect whereby the structure of the pad maintains a high degree of planarity which avoids the effect of a pad segment to conform or follow the contour of the rotor [4].

3. Rotor deflection and oscillation - Uniform pressure at engagement of a full circle pad reduces sensitivity to rotor deflection and oscillation – full circle pads can promote system stability by reducing frictional excitation [1], [2].

4. Uniform rotor wear eliminates the harshness related to excessive rotor runout.

<u>Thermal management solutions:</u>

Full circle friction contact results in uniform generation and distribution of heat at the pad/rotor interface and dissipates the heat over a significantly larger surface area. This results in lower pad temperatures which assist and promote the uniform evacuation of heat from both rotor and pads.

<u>Pad life and wear solutions:</u>

1. Pad configurations that are less sensitive to variations in rotor thickness reduce tendencies which accelerate both rotor and pad wear. Uniform rotor wear extends the life of rotors and friction materials.

2. Pad life is directly proportional to the volume of pad material available to be worn away. For equivalent wear life, the volume of a conventional pad may be redistributed over the surface of the full circle pad and the resulting thickness is reduced proportionally. This does not offer specific performance advantages of itself but provides manufacturing and marketing options. These include offering thicker pads having proportionally greater wear life, narrower radial pad sweep resulting in a larger effective radius for increased brake torque, or thicker pads of faster wearing materials that may be of lower bulk material cost.

3. Full circle pads eliminate the occurrence of pad taper as they are in constant contact during actuation and do not have leading and trailing edges which can result in non-uniform loading on conventional pads.

<u>Performance solutions:</u>

1. Increased brake torque due to amplified clamping forces permit smaller diameter rotors with equivalent stopping power.

2. Permits narrower caliper width due to thinner pad material and lack of axial piston requirement.

OBSTACLES TO AUTOMOTIVE APPLICATIONS OF FULL CIRCLE PADS:

Disc brakes with full circle pads or friction surfaces are not new. They have been universally fitted to large commercial, transport and military aircraft for many years, and are used in a wide range of industrial braking applications in construction, industrial, marine and mining equipment. The friction clutch, a torque transmission device closely related to the disc brake, is a good example of the accepted usage of full circle friction surfaces. Although the automotive industry understands the potential performance benefits adoption has been hindered by technical or cost penalties associated with the methods of applying clamping force developed thus far.

The following full circle pad engagement mechanisms have met with varying degrees of success:

1. Annular bladders or glands, hydraulically or pneumatically actuated.

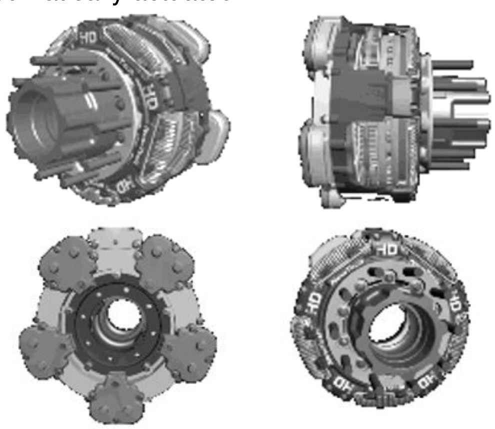

Figure 1: Four views of the NewTech full circle brake which employs an annular hydraulic bladder

2. Annular pistons, hydraulically or pneumatically actuated.
3. A radial array of hydraulic cylinders, as used in current aircraft brakes.

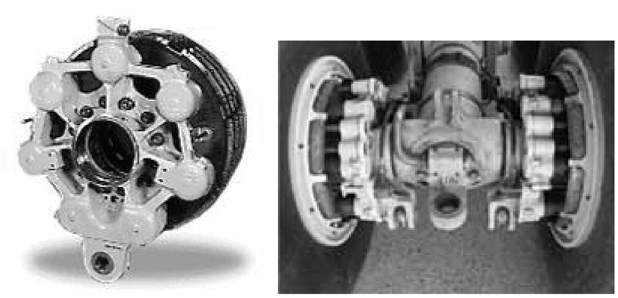

Figure 2: Multiple Piston Aircraft Brakes

The negative aspects of the abovementioned mechanisms, with respect to automotive applications, are:

- Annular pistons - expensive to manufacture; large piston seals are prone to damage and wear; hydraulic fluid vulnerable to overheating; sensitive to thermal expansion variations; not compatible with existing brake-by-wire electric actuation techniques.
- Annular bladders or diaphragms - prone to reliability issues - bladder material can be susceptible to heat deterioration and operational fatigue; hydraulic fluid vulnerable to overheating; sensitive to thermal expansion variations; not compatible with existing brake-by-wire electric actuation techniques.
- A radial array of hydraulic cylinders - requires a complex, multiple cylinder pressure plate housing structure; expensive to manufacture and maintain.

The major impediments to full circle pad usage in automotive brakes have been:

- The lack of a suitable means of brake pad engagement. The design challenge is to advance full circle pads into uniform rotor contact simply, economically and reliably.
- The manufacturing cost of a full circle brake has typically been higher than an equivalent conventional caliper brake, and while the major benefits derived are longer pad life and minimized NVH and thermal issues, the overriding factor for automotive brake manufacture is cost.

Full circle pad actuation mechanisms for automotive applications must therefore satisfy the following criteria:

- Comparable or reduced cost
- Comparable or reduced size and weight
- Industry-standard reliability
- Comparable or improved ease of service and repair
- Comparable or improved performance (brake torque and NVH)

A PRACTICAL SOLUTION

Braking Technologies Ltd. has developed a full circle pad actuation mechanism that is able to satisfy the abovementioned criteria and requirements. The method of actuation employs a coaxial helical mechanism to advance annular brake pads into contact with the rotor. Since the mechanism functions as a circular caliper it is named the CirCal™ brake system.

The CirCal™ brake, which has patents both granted and applied for, is based on proven mechanical principles with no dependence on exotic or breakthrough materials or technologies.

Figure 3: CirCal brake design for automotive applications

The CirCal brake's properties derive from its helical pad advance motion and its full circle brake pads. These allow for increased brake torque, improved heat dissipation, reduced complexity and size, fewer actuators, less weight and lower cost than conventional disc brake systems. Because the number of geometric variables has been increased, the CirCal brake design can be configured in a variety of ways to optimize performance, pad wear, rotor size, brake envelope, thermal dissipation, cost, and other criteria at the discretion of the designer.

The CirCal brake's helical action:

1. Enables uniform actuation pressure over the full friction contact area, providing even wear and homogenous heat generation, dispersion, and dissipation.

2. Amplifies the actuation force as a result of its inherent mechanical advantage

3. Requires a single actuator; additional actuators can be employed for redundancy or for added force.

4. Is fundamentally a mechanical action compatible with direct mechanical, hydraulic-over-mechanical, pneumatic-over-mechanical or electric-over-mechanical configurations.

5. Is fully compatible with Antilock Braking Systems (ABS), Brake-by-Wire (EBS), Electronic Stability Control (ESC), Automatic Brake Assist Systems, and Traction Control Systems

6. Allows the actuator to be thermally isolated from the active friction surfaces to avoid thermal effects on fluids or related components.

7. Allows the actuator to be a separate component for replacement and service without the cost of replacing the rest of the caliper assembly.

The CirCal design can provide higher performance brakes in the same working envelope as a conventional caliper disc brake, or a more compact brake of equal or better performance than conventional caliper disc brakes. In heavy duty applications the CirCal brake can provide the stopping power and performance of disc brakes with the long lining life of large surface area drum brakes.

Figure 4: Full circle pads can comprise a single annular ring or individual pad segments

The CirCal coaxial helical brake functions as follows:

a) The helical action amplifies actuation force in the same manner as a screw thread provides much higher mechanical leverage, enabling higher brake torque for a particular rotor or equivalent brake torque for a smaller diameter rotor.

b) The helical action requires a single actuator - mechanical, hydraulic, pneumatic, or electric; additional actuators can be employed for redundancy or for increased force.

c) For typical service brake operation the rotating pressure plate is decoupled from the pad structure via low friction interstitial slip surfaces. The slip surfaces allow the brake torque to be transmitted directly from the pad backing plate to the spindle or axle structure.

d) The helical mechanism's inherent self-energizing property can be utilized to provide powerful and rapid braking in emergency and safety brake applications involving rotation in one direction only.

e) Low friction coatings are recommended to be used on the helical thread and the pressure-plate-to-pad-backing-plate wear surfaces to minimize parasitic friction losses in these sliding and load bearing components. Other means of helical guidance can utilize bearings or track rollers with a corresponding tradeoff between cost and parasitic friction.

f) Protection of the helical mechanism, whether threads or rolling elements, is effected by exclusion seals at the inner and outer boundaries of the helical section. The seals prevent external contaminants such as dust, oils, and worn brake pad material from compromising the helical feature and reducing its wear life or altering its actuation efficiency.

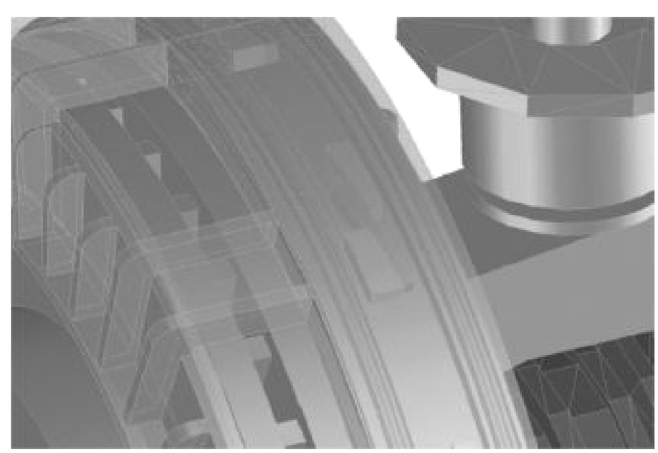

Figure 5: The CirCal brake’s coaxial helical thread segments and exclusion seals

Advantages that can be derived from the use of the CirCal brake design:

1. Performance:

- The CirCal system is compatible with multiple rotors and stators as commonly configured for aircraft brakes.

- The CirCal brake can be configured to produce more torque through the mechanical advantage of the helical advance mechanism.

- The CirCal brake can utilize more aggressive friction materials that may exhibit high wear rates: The annular brake pads provide maximum friction surface area. This allows the use of pad materials of a substantially higher friction coefficient (mu) than conventional brake pads while still providing acceptable pad life. Higher mu materials generate higher brake torque resulting in enhanced performance over a conventional brake of the same size, or equivalent performance with a more compact, lighter and lower cost system.

2. Noise, Vibration, Harshness: There are multiple effects of continuous contact pads which favorably affect the NVH characteristics evidenced in many conventional caliper disc brakes.

- The helical advance mechanism assures a uniform application of the clamping force between pad and rotor surface. This uniformity minimizes any eccentric effects of the brake torque and the attendant oscillations that occur.

- Conventional caliper disc brakes can encounter a singularity event on each rotation that occurs when a discrete location on the rotor of rotor thickness variation, surface friction change, hardness difference, sudden thermal gradient, or other rotor characteristic encounters a leading or trailing edge of a brake pad. Such encounters can initiate displacements or reactive forces which are then transmitted through the brake structure and are identified as NVH issues. The circular, uniformly applied brake pads maintain full contact with the rotor during application and the singularity events do not occur. This unique characteristic can inhibit noise inducing vibrations and oscillations, reduce hot-spot judder, and decrease rotor deflection.

- Continuous circular contact of the pad also maintains uniform rotor wear which eliminates the harshness associated with caliper system runout and extends the life of friction materials and rotors.

- Increased brake torque due to amplified clamping forces permit lower mu pad materials with equivalent stopping power. Lower mu materials inhibit noise creation and also reduce pad and rotor wear.

3. Thermal Management:

- The distribution of material volume in full circle pads results in significantly thinner pads which allows efficient heat conduction through the pad material into the pad backing plates and brake structure for improved dissipation. Heat conducted into the backing plates and subsequently dispersed via and dissipated from the brake structure means less heat absorbed by the pad material and rotor. Furthermore, since heat is uniformly distributed over the large surface area of the annular brake pads the overall pad temperature is reduced. Alternate pad materials with higher thermal conductivity can be further utilized to change the balance of heat transfer and dissipation.

- The CirCal system's actuator is typically located behind the pressure plate and so is isolated from the pads and rotor heat generation source, thus preventing overheating of hydraulic fluid, or electric linear actuators in brake-by-wire systems.

- The isolated location of the actuator/s permits the CirCal brake design to conduct heat through the pads into the pad backing plates and into the brake housing structure for maximized dissipation. The housing structure can be optimally designed and shaped to maximize heat flux and dissipation. Fins, ribs and vents can be incorporated to increase the outer surface area and to assist cooling airflow.

- The annular pad's significantly larger surface area allows the rotor's swept depth to be reduced in order to optimize airflow through the rotor's internal vents. Even if the swept depth were reduced by 50% there would still be 5 to 6 times more pad contact area than conventional pads. This reduction in the swept depth may be implemented from the maximum radius of the rotor, resulting in a larger neutral radius at which the brake torque is applied, or the reduction may be used to reduce the overall rotor diameter, thereby reducing the total size of the entire brake structure.

- With full circle pads the uniform dispersion of heat through the pad material into the pad backing plates allows the brake support structure to dissipate the heat over a larger surface.

- Narrower radial contact face: as described earlier, the full circle pad structure can be designed to redistribute the given wear volume of a conventional pad onto the full circle of the rotor. At the discretion of the designer, the radial distance of contact can be varied with the corresponding change in pad thickness to maintain wear life. As the radial distance of contact is reduced, the effective brake torque radius is increased, improving brake performance. With the reduced radial contact distance, the designer has the option of altering the rotor structure such that the inside radius of a vented rotor is larger while maintaining the same outside radius as the original. This leads to shorter air paths along the rotor vanes and permits optimization of the vanes over a wider range of rotation speeds.

- Wider vented rotors: The thinner pads that result from distributing the conventional pad wear volume around full circle pads also yield a reduction in the overall width of the brake structure. Correspondingly, the brake structure can be maintained at the original width with the thinner pads permitting the use of wider rotors. This increase in rotor width can be further exploited to optimize the thermal performance of the rotor with larger, more efficient air paths between the vanes, even to the point of incorporating additional dissipating surfaces inside the air passages of the rotor. This is borne out by AP Racing, a manufacturer of high performance rotors, recently introducing their line of "Wide Disc" rotors with geometries as described [5].

4. Size, weight and packaging: Permits narrower caliper width due to thinner pad material and lack of axial pistons. Increased brake torque due to amplified clamping forces permit smaller diameter rotors with equivalent stopping power.

5. Since pad volume equals pad life, the CirCal brake's large pad surface area - about 8 to 10 times that of conventional brake pads - enables a relatively small increase in pad depth to significantly increase pad volume and therefore pad longevity.

6. Simplicity of actuator design and location: The CirCal system requires a single actuator, typically located behind the pressure plate, allowing ease of assembly and service. A single hydraulic cylinder permits less piston seal length, leading to improved reliability. The operation of the actuator does not require it to be separate from the housing and decisions regarding implementation are entirely at the discretion of the designer for strategic business or service purposes.

7. System advantages: Amplified actuation force permits the use of smaller vacuum boosters. Increased brake torque due to amplified clamping forces permit smaller diameter, lighter weight rotors which enable smaller wheels and tires, and corresponding reduced unsprung weight.

8. Manufacturing options and opportunities: the annular configuration of the brake structure and brake pads together with the actuator location flexibility permits a variety of manufacturing processes and materials beyond those common to conventional calipers to achieve cost and weight savings.

Applications

The CirCal brake system can be configured to meet a wide range of braking requirements, etc., etc.

- Cars, SUVs, Light trucks
- Heavy vehicles: trucks, construction, military, etc.
- Aircraft, including helicopter rotor brakes
- Industrial vehicles, machinery and equipment

CONCLUSION

This paper presents the performance advantages that full circle brake pads can offer in automotive disc brake applications, and proposes that these benefits can be economically and reliably achieved using a mechanical coaxial helical mechanism such as the CirCal brake system to engage the annular pads into rotor contact.

As with all engineering solutions, choices and tradeoffs between cost, weight, size, performance and reliability must be made. The coaxial helical mechanism with its full circle pad configuration offers the automotive brake designer a far broader range of choices than traditional caliper designs, allowing a more refined decision process to configure a brake with appropriate feature, function, and financial benefits. Such configurations, for example, can include better performance in the same brake envelope, obviating the need for larger wheels and tires. Or they can permit smaller diameter rotors thereby allowing the use of smaller wheels and tires and the accompanying cost and weight reductions.

Because full circle pad brakes thus far have not been successfully adopted for motor vehicle use, there is a dearth of data and information on NVH issues with regard to the moderating effect that full circle pads can provide. This needs to receive much greater scrutiny in the future to validate the potential full circle pad utilization represents for the automotive brake industry.

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