

Optimized Caliper Design for Low Drag Using DFSS Method

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ABSTRACT

Limiting residual drag torque and fluid displacement is a major requirement of a caliper brake as they are related to the fuel efficiency and the safety of a vehicle. However, it is difficult to simultaneously reduce both the drag torque and the fluid displacement since improving one tends to degrade the other.

This paper investigates a caliper with a high residual drag torque. DFSS (Design for Six Sigma) method was implemented to identify all major factors and the design optimization was performed to achieve a low drag caliper. The prototype was created with the desirable design factors identified in the study and the dynamometer tests confirmed that it is possible to achieve a low drag caliper without sacrificing the fluid displacement.

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INTRODUCTION

In a brake system with caliper brake assembly and rotor, the brake torque is generated by the clamping force between the rotor and the lining utilizing the hydraulic pressure inside caliper housing. The ideal condition on release of the hydraulic pressure is clamp force-free condition, so that the brake system does not have residual drag torque. However, residual clamp force does exist in real brake system due to energy loss and causes drag torque.

The brake drag torque is a major requirement of a caliper brake, as it is directly related with the fuel efficiency and it can also induce the rotor thickness variation and then brake pulsation. However, it is not easy to control because it has conflicting relation with pedal travel.

To design a low drag caliper, it is a direct and general method to increase the piston roll back by optimization of the seal piston, seal and the seal groove configuration. However the increase piston roll back increases the fluid displacement and then the pedal travel. If the piston roll back can be used up by the spring back of the other components of a caliper, it can also cause high brake drag.

Previous papers focused on piston, seal and seal groove configuration or the housing and lining stiffness to achieve an

optimized low drag caliper. However, controlling housing stiffness is limited by mass and package requirements which are getting more and more severe. As stiff pad can make the caliper to be prone to squeal noise, pad stiffness is not often available as a control factor.

This paper investigates a caliper with a high residual drag torque. DFSS (Design for Six Sigma) method was implemented to identify all major factors and the design optimization was performed to achieve a low drag caliper.

Drag test was performed with burnished pads at high speed conditioned after released from various fluid pressures. Fluid displacements were also measured at dynamic condition simulating vehicle condition with burnished pads.

TEST PROCEDURE

Small single bore floating caliper was tested. Same caliper was used to evaluate fluid displacement and drag torque to have consistency.

Fluid Displacement Measurement

A caliper was installed to a brake corner fixture. Rotor run-out was adjusted to $50 \pm 5 \mu\text{m}$.

Brake pads were burnished with 200 brake stops, and fluid displacement was measured at 500, 5,000, 12,000kpa when the braking was applied from initial speed of 100kph at a inertia dynamometer as shown at [figure 1](#)



Figure 1. Inertia Dynamometer for measuring dynamic fluid displacement

Drag Torque Measurement

After fluid displacements were measured, the caliper and the rotor were uninstalled from the corner, and installed at drag bench to measure drag torque.

500kPa fluid pressure was applied to the caliper and released prior to drag measurement. The drag torque was measured at 400 rpm. The measurement were repeated after released from 2,500, 5,000, 12,000kPa pre-pressure to check the effect of the pressure. All the measurements above were repeated at 800rpm.



Figure 2. Drag Bench

PROBLEM DEFINITION

After measuring the fluid displacement and the drag torque with Left hand and right hand side calipers, fluid displacement and drag torque target were determined.

Dynamic fluid displacement measurements were shown in [figure 3](#) and [table 1](#)

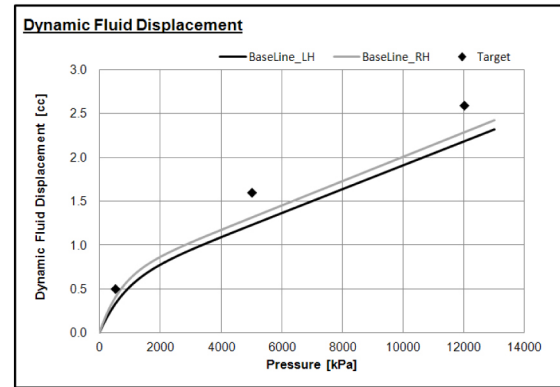


Figure 3. Dynamic fluid displacement of baseline caliper

Table 1. Dynamic fluid displacement of baseline caliper

Pressure [kPa]	Dynamic Fluid Displacement [cc]		
	LH	RH	Target
500	0.32	0.39	0.5
5,000	1.23	1.31	1.6
12,000	2.18	2.29	2.6

Fluid displacement target was taken to minimize the fluid displacement increase due to change to the caliper to decrease the drag torque. [Figure 4](#), [5](#) and [table 2](#) show drag torque measurements at drag bench using the brake caliper assembly and the rotor which were uninstalled from inertia dynamometer after dynamic fluid displacement were measured.

Although baseline caliper met the dynamic fluid displacement target, it did not meet drag torque target at entire conditions. Baseline caliper was defined as high drag caliper and investigated to find factors to reduce the drag torque while influence on fluid displacement was minimized. Most caliper design parameters including seal groove configuration were considered.

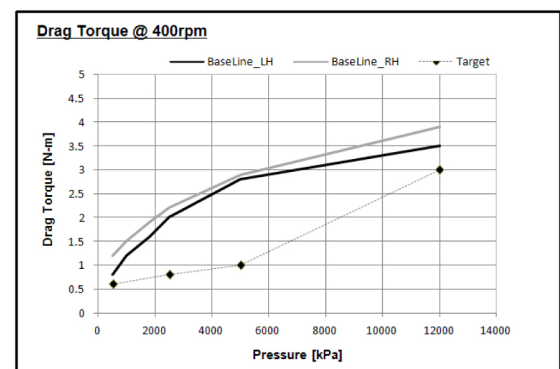


Figure 4. Drag Torque at 400rpm of baseline & Drag Torque at 800rpm of baseline

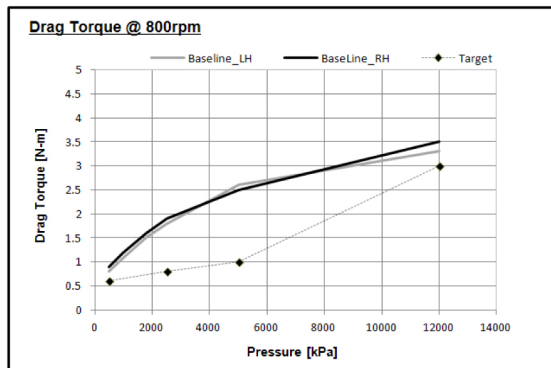


Figure 5. Drag Torque at 400rpm of baseline & Drag Torque at 800rpm of baseline

Table 2. Drag Torque of baseline caliper

Pressure [kPa]	Drag Torque [N-m]				Target
	400rpm		800rpm		
	LH	RH	LH	RH	
1,000	0.8	1.2	0.8	0.9	0.6
2,500	2.0	2.2	1.8	1.9	0.8
5,000	2.8	2.9	2.6	2.5	1.0
12,000	3.5	3.9	3.3	3.5	3.0

ORGANIZATION OF P-DIAGRAM

Control Factor

Factors for drag torque were reviewed and scope tree was drawn categorizing them into three groups; clearance, sliding resistance and installation (Figure 6). As the caliper investigated was under development for mass production, it is decided to avoid any factor which could affect the cost or the timing.

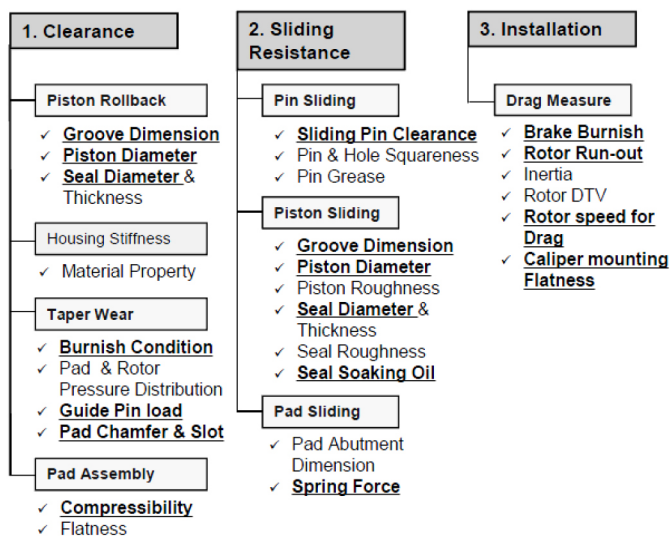


Figure 6. Scope Tree

Table 3. Control Factor

Control Factor	Level (Blue Font : Current Design)	
	1	2
A Pin Hole Diameter	Ø10.0mm	Ø10.1mm
B Bush Pin/Solid Pin	Leading : Solid	Leading : Bush
	Trailing : Bush	Trailing : Solid
C Chamfer of Seal Groove	0.45mm	0.6mm
D Piston Diameter	Ø53.87mm	Ø53.92mm
E Seal Outer Diameter	Ø64.8mm	Ø65.0mm
F Soaking Oil for Seal	Lubricant A	Lubricant B
G Pad Chamfer	None	Chamfer
H Pad Slot	None	Slot
J Noise Shim	High Damping	Low Damping
K Spring Force	Current Condition	Leading/Trailing Different Force

Clearance category includes piston rollback, taper wear and pad assembly. Sliding resistance includes pin, piston and pad sliding. Installation is defined as noise factors for the drag torque and the displacement is measured at dynamometer, not on the vehicle

10 factors shown in table 3 were selected, and each factor was evaluated with 2 levels. 11 control factors were considered at the beginning and "I" factor (Rotor run-out) was moved to noise because it is uncontrolled factor for caliper side.

Factors marking with blue color are current design factor and black ones are parametric factor.

A and B factors are related to pin sliding. C, D and E factors are related to piston roll-back. F factor is related to piston sliding resistance. G and H factors are selected to reduce the effect of pad taper wear. J factor is related to compressibility of the pad assembly. To prevent side effect of lining compressibility change, anti-noise shim is controlled to have different level of pad assembly compressibility.

K factor is selected to verify the effect of pad sliding resistance. Spring force at leading side is reduced to have lower pad sliding force.

Noise Factor

As previously mentioned, the measurements of drag torque and fluid displacement were performed by dynamometer simulation, not directly on vehicle. Installation condition to the dynamometer of rotor run-out and caliper mounting flatness are selected as noise factor. Rotor speed of drag measurements are selected as an additional noise factor. (Table 4, 5)

30 µm and 80µm are selected as two levels of the rotor run-out. 0.09mm max and 0.2mm are selected as two levels of caliper mounting flatness. 400 rpm and 800rpm is selected as two levels of rotor speed for drag torque measurement.