

Identification of Brake-drag Mechanism in Coasting-down Mode and Proposal of Brake-drag Stabilization and Reduction Methods

Yasushi KOBAYASHI*

Yuta HIGUCHI*

Naoki NAKAMURA**

ABSTRACT

The displacement of brake parts and values for brake drag were monitored during bench testing in coasting-down mode. In this mode, the brake-drag measurement process is preceded by a brake operation process while the vehicle is running warm, and at this time the brake disks undergo heat deformation as their temperatures rise. The subsequent brake-drag measurement process involves a reduction in disk temperature. This is accompanied by a return of the disk from its heat-deformed state so that the disk approaches more closely to the inner pad, and when it impinges on the pad, drag occurs. Also, when the inclination of the inner brake pad to the brake disk at that time is such that there is less clearance between the disk and the pad on the rotation input side (leading side) and there is more clearance on the rotation output side (trailing side), the pad is drawn toward the disk so that the drag suddenly increases. This force that draws the pad and disk together is the force of the vacuum pressure generated between them. This force was successfully used to both stabilize and reduce brake drag by establishing a setting that balances the load from the pad return spring, which is a structure for the purpose of reducing drag, between the leading side and trailing side, and by establishing guidelines for the amounts of caliper piston rollback and caliper body deformation.

1. Introduction

Growing demands for increasing fuel economy with a view to global environmental protection are being accompanied by proposals for various drag reduction methods for disk brakes. The mode used to measure running resistance, which is necessary for projecting fuel economy, is the coasting-down (C/D) mode^{(1), (2)}. Since this was measured using actual vehicles that were being driven, measurement was influenced by various factors such as road surface and air resistance, resulting in the measured brake drag being unstable. Here, the mode was transposed to a bench test and analyzed. This reduced the variations that result from test conditions, but variations were still found in the measurement results. In other words, even though attempts were made to ascertain the actual value of brake drag for each specification, valid figures could not readily be determined. Furthermore, even when new methods for reducing drag were proposed, their effectiveness could not readily be evaluated in a quantitative manner. Stabilization of drag was therefore sought by bench testing to clarify the mechanism of brake drag during mode testing and identify

the main factors that influence the resulting drag values. On that basis, specifications for further reduced drag could then be created. This development project is intended to yield a clearer understanding of front brakes of the single-piston pin-slide caliper type, which are the main type used on mass-production vehicles.

2. Development Goals

The following three points are the main objectives of this development project.

- (1) Clarification of the drag mechanism
- (2) Identification of the main factors in drag
- (3) Proposal of methods for stabilizing and reducing drag

The stable reduction of brake drag is crucial for increasing fuel economy. Figure 1 shows the basic brake caliper structure, and Fig. 2 shows an overview of the general mechanism of brake drag as it has been understood to date. When the brake is released from its operational state, the caliper piston rolls back because of the elastic deformation of the piston seal (piston R/B) and returns to its position that is removed from the disk. At this point, the

* Automobile R&D Center

** Nissin Kogyo Co., Ltd.

pad remains in contact with the disk, and this resistance that is generated when the brake is not operating is brake drag^{(3), (4)}. There are also calipers now that reduce drag by a mechanism that uses a spring to move the pad away from the disk together with the piston (Figs. 3 and 4), but the measured drag was not stable.

Figure 5 shows the results for vehicle speed and brake pad temperature measurements when the C/D mode was transposed onto a bench test. It is characteristic of this approach that the brake drag measurement process is preceded by vehicle operation to warm up the engine, and this process involves repeated operation of the brakes. After that, the vehicle was allowed to decelerate naturally from 140 km/h to 0 km/h. This natural deceleration process was repeated five times and the resistance was measured with and without brake pads each time, the difference being

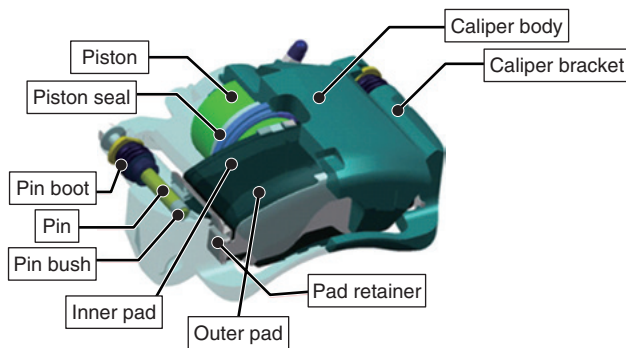


Fig. 1 Basic caliper structure

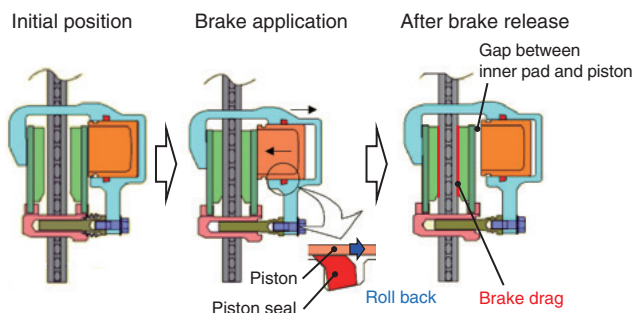


Fig. 2 Conventional brake drag theory

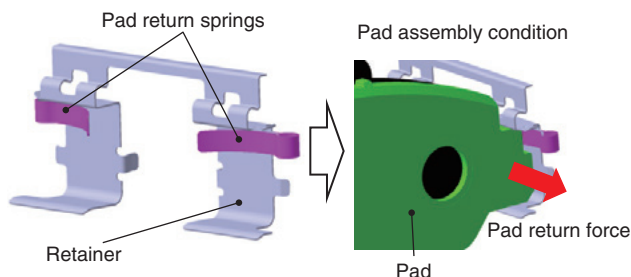


Fig. 3 Example of pad return spring structure

taken as the drag value. It is apparent from this figure that the brake pad temperature rises in the process of repeated brake operation.

Figure 6 shows data on brake drag derived from measurement of a single front wheel during bench testing in C/D mode (the figure shows the data for the wheel on one side multiplied by two). During the first brake drag

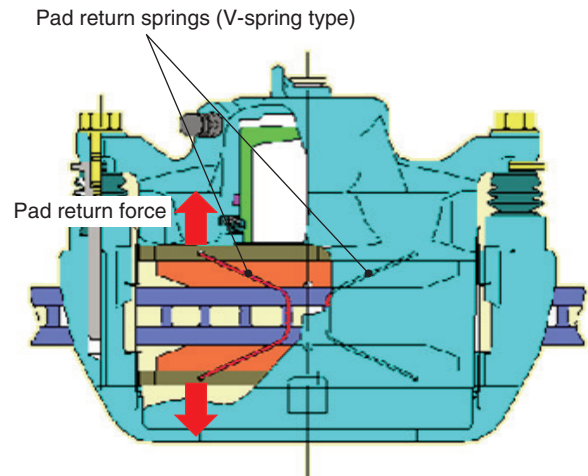


Fig. 4 Example of pad return spring structure (V-spring type)

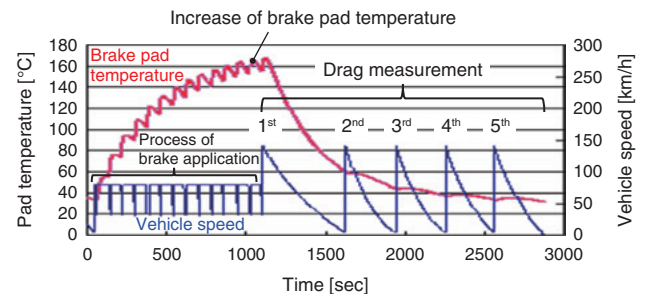


Fig. 5 Bench test condition in C/D mode

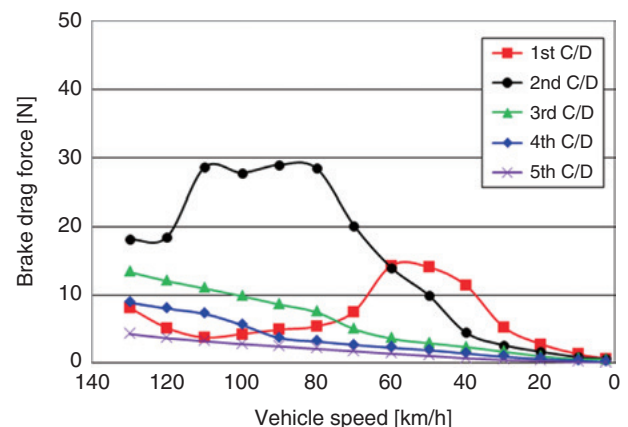


Fig. 6 Brake drag force variability in each C/D

measurement (1st C/D), the drag suddenly increased partway through. There was also instability during the second measurement, but as the drag increased, the vehicle speed decreased and the drag then diminished with it. From the third measurement on, the value decreases gradually and becomes more stable.

The purpose of this research was to identify the causal factors in these phenomena and to propose methods for stabilizing and reducing brake drag.

3. Clarification of the Brake Drag Mechanism

3.1. Confirmation of Drag by Means of a Modified Caliper

Figure 7 shows the test caliper used to clarify the drag mechanism. The purpose of this caliper is to confirm whether drag is occurring from the inner pad or from the outer pad. A mass-production caliper was therefore modified and load cells were arranged so that the resistance force tangential to the direction of rotation could be measured separately on the inner pad and the outer pad.

Figure 8 shows the measurement data for brake drag force during bench testing in C/D mode using the modified caliper. Drag force was not detected on the outer pad; it was detected only on the inner pad.

3.2. Measurement of Displacement

In order to confirm the reason that drag occurred only on the inner pad, mass-production parts were used and

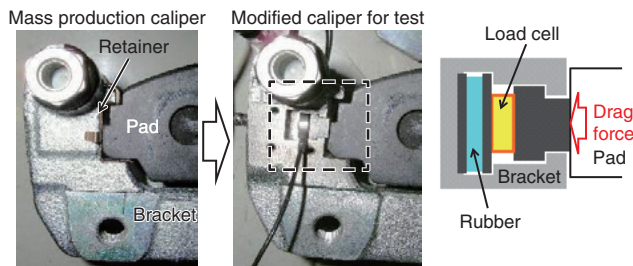


Fig. 7 Test caliper structure

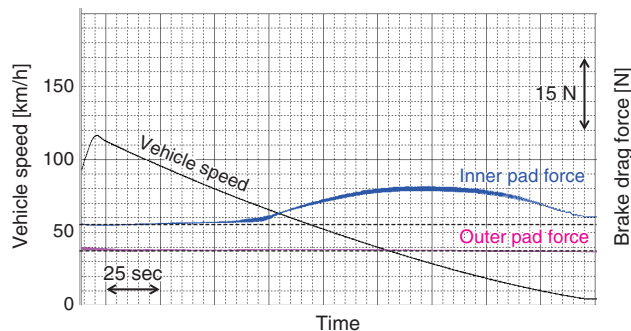


Fig. 8 Brake drag torque of each inner and outer pad in C/D mode

displacement was measured at two points each on the caliper body, inner pad, outer pad, and disk while bench testing in C/D mode. **Figure 9** shows the measurement points. **Figure 10** shows the position of each part measured during those processes of mode testing as obtained from those measurements.

The disk position in the second stage in Fig. 10 indicates that the disk undergoes heat deformation toward the outer pad as a result of the rise in disk temperature from the repeated brake operation process preceding brake drag measurement. Following this disk displacement, the caliper body as well as the inner pad and outer pad move toward the outside. However, as is evident from the third stage in Fig. 10, where brake drag measurement takes place, the temperature of the disk then decreases so that the disk shape, which had been deformed, return toward the inner pad. When this happens, the disk presses against the inner pad, generating drag force. This behavior is thought to be the reason that drag force was not detected except from the inner pad in Fig. 8.

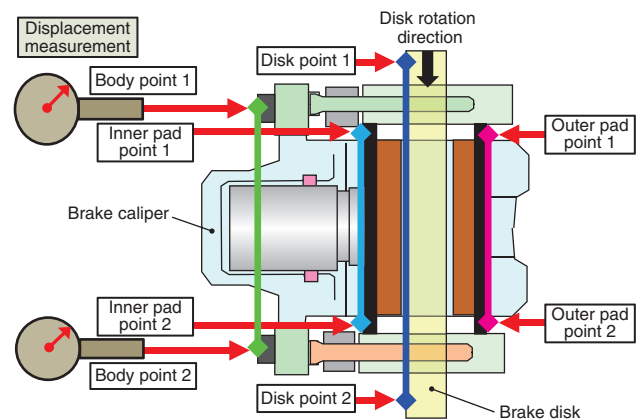


Fig. 9 Measurement points of each part

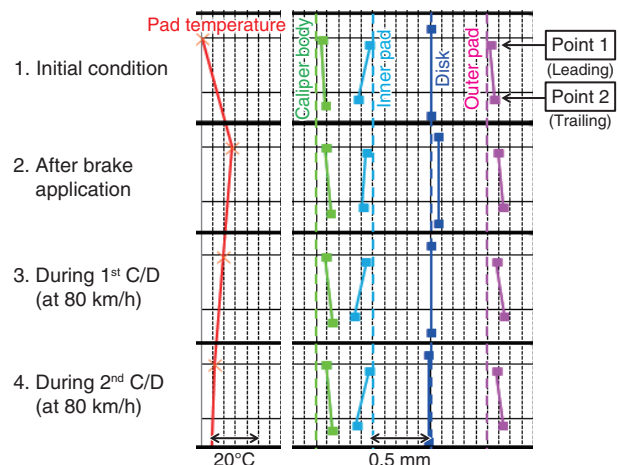


Fig. 10 Position of each part in C/D

Figure 11 shows the displacement over time resulting from heat deformation in the disk during C/D mode testing. The greatest deformation occurs on the outer-pad side of the disk during the repeated braking operation⁽⁵⁾. After that, the disk cools and returns to its original shape while the brake is not being operated. When this happens, some heat expansion of the disk surface in the thickness direction also occurs, and this is one reason why the disk surface is positioned more toward the inner-pad side when the first and second brake drag measurements are made than it was initially. From the third iteration on, further cooling takes place and the disk returns to its initial position. This also clarifies the reason for the drag occurring in the first and second iterations in Fig. 6, where it had been considered variations, as well as the reason why the drag diminished from the third iteration on.

3.3. Vacuum Pressure

Figure 12 shows displacement of the inner pad at the trailing side with respect to the direction of disk rotation (Point 2), displacement of the disk, vehicle speed, and drag force over time during the process of brake drag measurement in C/D mode. It is apparent that when the disk approaches more closely to the inner-pad side during brake drag measurement, the position of the inner pad on the rotation trailing side moves in the direction of the disk so that drag increases. The pad that moves in this way has a tendency to suddenly return to its starting position when the vehicle speed diminishes.

Figures 13 and 14 show the calculation results for fluid analysis of pad inclination and vacuum pressure generation. The rotation leading side of the inner pad is closer to the disk than the trailing side, and when the pad is inclined in this way, a force due to vacuum pressure is generated between the inner pad and the disk. When the pad is inclined in this way but there is sufficient clearance between it and the disk, almost no vacuum pressure is generated (Fig. 13). Figure 15 shows the results for measurement of vacuum pressure made using a pressure sensor actually embedded in the pad. The inner pad inclination was set so that the leading side closes to zero clearance at the equivalent of 160 km/h. This confirmed that drag force

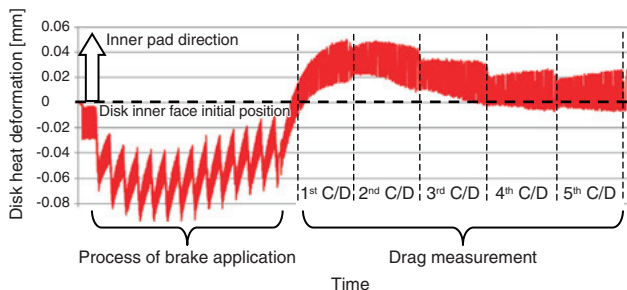


Fig. 11 Disk heat deformation in C/D

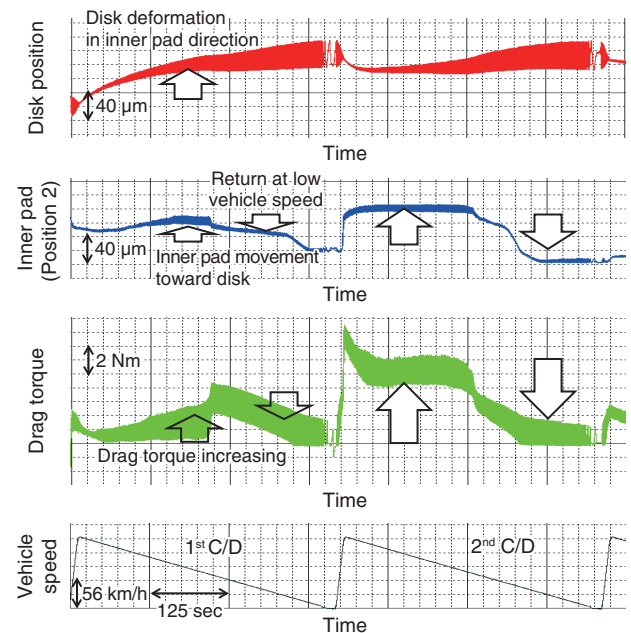


Fig. 12 Displacement behavior of each part in C/D mode

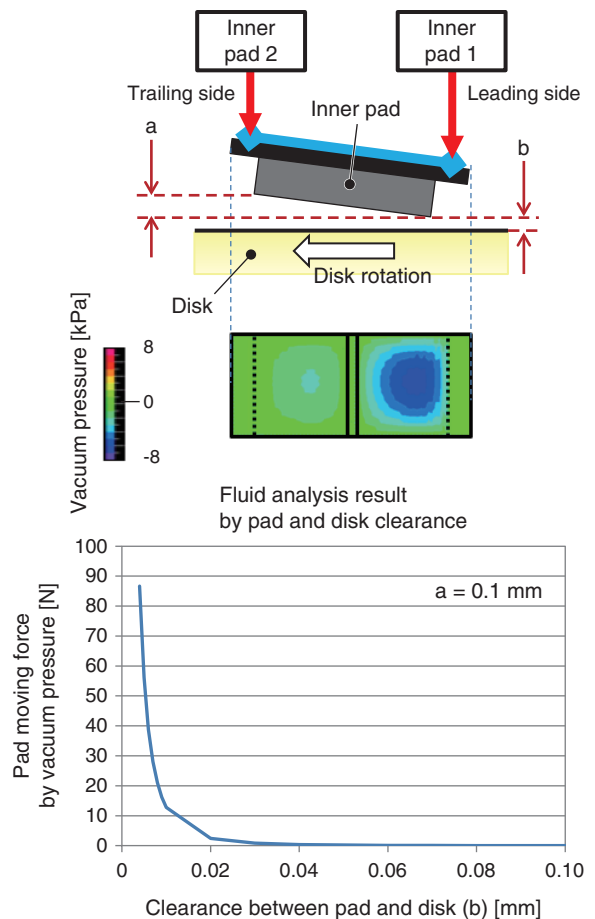


Fig. 13 Vacuum force simulation by pad and disk clearance

was generated at the same time that vacuum pressure was detected. It appears likely that the force of this vacuum pressure draws the inner pad against the disk, triggering the increase in drag.

3.4. Pad Inclination and Drag

Figure 16 shows sample data from the various brake drag measurements made to this point consolidated in terms of the inner pad inclination immediately before brake drag measurement. This shows that even when the inner pad and disk clearance immediately before brake drag measurement is small, drag does not increase except when the pad inclination is such that the clearance is smaller on the leading side than on the trailing side. As the drag tendency in Fig. 16 also shows, the magnitude of the drag values are not in direct proportion to the clearance between the inner pad and the disk or the angle of inclination of the inner pad. This suggests that the phenomenon of sudden

increases or decreases in drag of the kind shown by the data in Fig. 6 is a result of the sudden movement of the inner pad shown in Fig. 12, and that the cause is vacuum pressure.

The above findings on the mechanism of brake drag in C/D mode are put into organized form as follows. Heat deformation occurs in the disk in the brake operation process during mode testing. In the state of brake non-operation that follows, the disk cools and returns to its former shape, and when the disk presses against the inner pad, drag force is generated. At that time, the inner pad is inclined to the disk at an angle such that the leading side approaches zero clearance. When this happens, vacuum pressure is generated between the disk and the inner pad, and the inner pad is suddenly drawn against the disk, resulting in the inner pad and disk coming into contact. This is thought to be why the brake drag value suddenly increases.

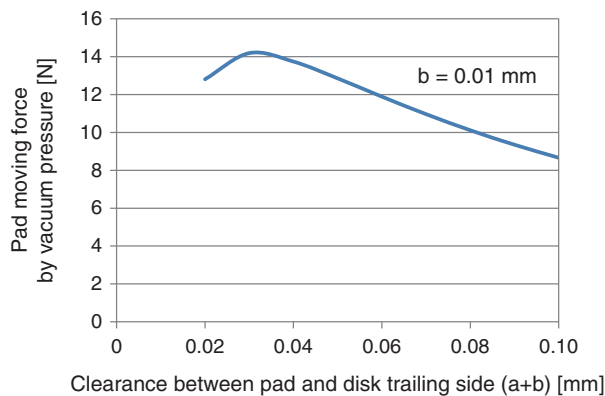


Fig. 14 Vacuum force simulation by pad inclination

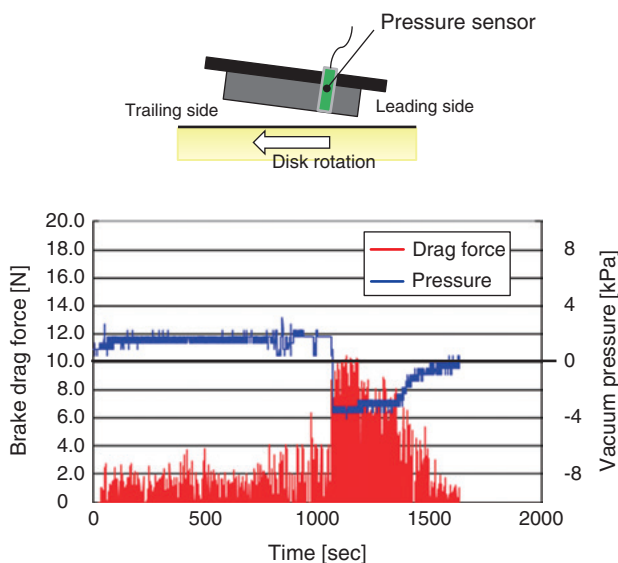


Fig. 15 Vacuum pressure between pad and disk

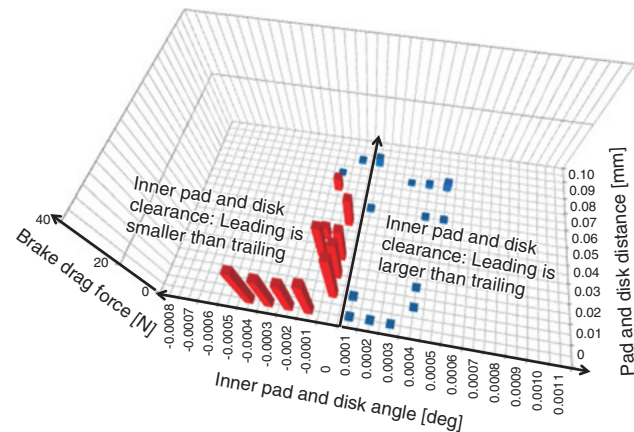


Fig. 16 Brake drag force by inner pad posture

4. Identification of the Main Factors in Drag

A parameter study of caliper component parts was carried out in order to identify the main factors causing drag to increase. This was approached in terms of the mechanism of drag generation described in the preceding chapter, and parameters related to pad inclination and to clearance between the disk and the inner pad were identified. The influence on drag value due to the accuracy of these parts and the differences between specifications were verified. There are also items that vary with the vehicle model, because of the actual vehicle layout and other such reasons, such as the caliper mounting position and the pin clearance in the caliper bracket hole (tight or loose pin configuration). The influence of these items on drag values due to the difference between leading side and trailing side was verified. The verified parameter items are

Table 1 Parameter study items for caliper

Classification	Factor	Items
Accuracy	Pad inclination	Pad return spring force
Specification	Clearance between disk and pad	Piston roll back
		Body deformation
Installation condition	Body position	Car installation position
		Tight and loose pin application
		Car installation angle

shown in Table 1.

Findings obtained by the parameter study are as follows.

The pad return spring has a considerable effect on the inner pad inclination, and the load ratio of the return spring between the leading side and trailing side was varied to confirm the influence on brake drag value (Fig. 17). It can be seen that a higher pad return load on the leading side yields a lower, more stable drag value than it does on the trailing side. The vertical axis shows the inclination of the inner pad with respect to the disk, and a correlation between the pad return spring leading-trailing load ratio and the pad inclination can also be confirmed. This was confirmed using four different types of caliper, and all displayed the same tendency. However, the return spring load must be set at or below the range of the piston rollback load, or the inner pad will push back the piston, which would end up increasing the number of invalid strokes during brake operation.

Next, Fig. 18 shows confirmation of the influence on drag from calipers with different specifications for the differences between piston R/B and caliper body deformation, which are plotted on the horizontal axis. The difference between piston R/B and caliper body deformation is the size of the clearance that can exist between the inner pad and the disk after the brakes are released. Each piston R/B and caliper body deformation value are considered

important in terms of determining caliper specifications, and they are carefully managed. Since the disk experiences heat deformation during the C/D mode, further subtracting the disk heat deformation from the difference between the piston R/B and caliper body deformation yields a value that is the remaining clearance between the inner pad and the disk. When the disk heat deformation is taken as a fixed value, as in Fig. 18, the drag will be low and stable as long as a sufficient difference is maintained when caliper body deformation is subtracted from piston R/B. This shows that a greater piston R/B is preferable in order to achieve a lower drag value. When the brake is not operating, however, the piston is in a position more distant from the disk. This means that the piston has a greater distance to travel toward the disk when the brake is operated, increasing the amount of brake pedal operation and causing a reduction in operating feel. A smaller caliper body deformation will also yield lower drag, but reducing caliper body deformation will generally involve increasing its thickness and will require increasing the weight of its parts. In C/D mode operation, where the disk undergoes a process of heat deformation, reducing the heat deformation of the disk contributes to a reduction in drag. However, methods for accomplishing this will generally require increasing the heat capacity, which tends to increase the weight of the parts. What this means, therefore, is that design with an optimal balance of these factors is important for reducing brake drag and for maintaining the competitiveness of brake-part weight and operating feel.

Figure 19 shows how drag is influenced by differences in the angle at which the caliper is mounted on the vehicle with respect to the axis of rotation of the disk. It is clear that varying the angle of installation on the vehicle has little influence on drag.

Figure 20 further shows the results for drag when the caliper is installed in two different positions with respect to the axis of rotation of the disk (installed in front of the axis or behind the axis), and each of these is paired with caliper pins of two different types (tight or loose) in terms of the clearance in a radial direction between the pin and the pin hole at

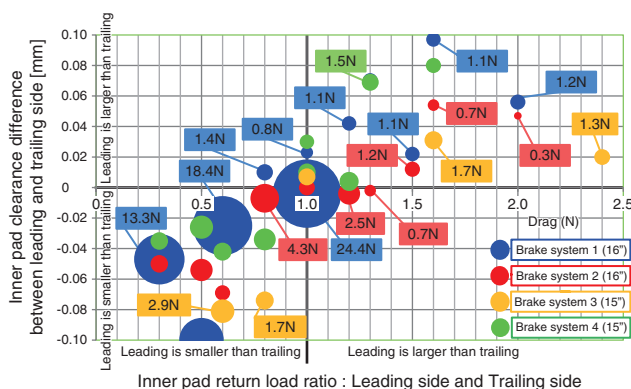


Fig. 17 Brake drag force by pad return spring load balance

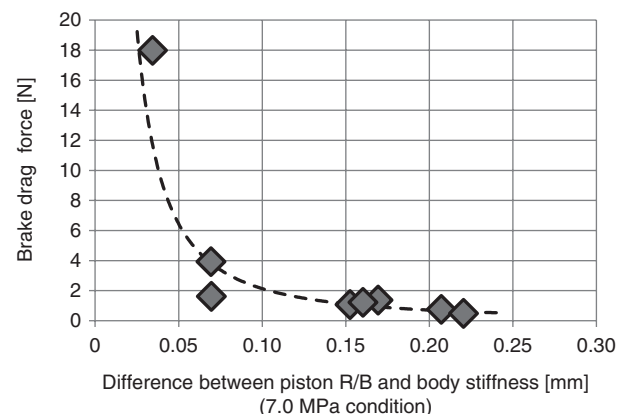


Fig. 18 Brake drag force by piston R/B and body deformation

the leading side and trailing side. The overall drag force is relatively low, at 2 N or less, indicating that these factors have only slight influence on drag. These findings show that the angle of caliper installation on the vehicle and the change in caliper pin type has only slight influence on the drag value. The results here indicate that the caliper installation angle may be varied for layout convenience according to the vehicle model and still make only a slight contribution to the drag value. It is apparent that a greater contribution is made by elements of standalone caliper performance, namely pad return load, piston R/B, and body deformation (stiffness).

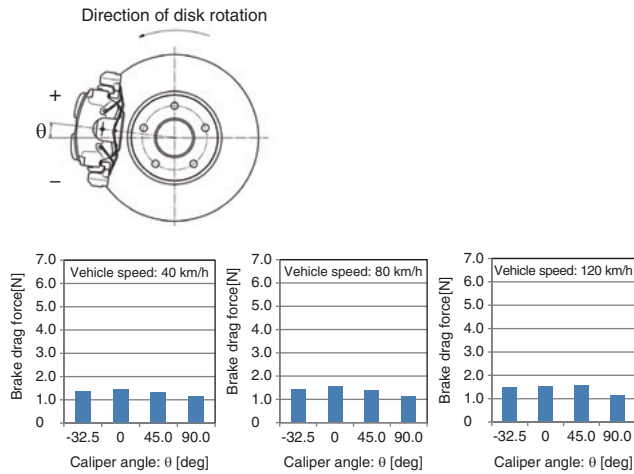


Fig. 19 Brake drag force by caliper installation angle

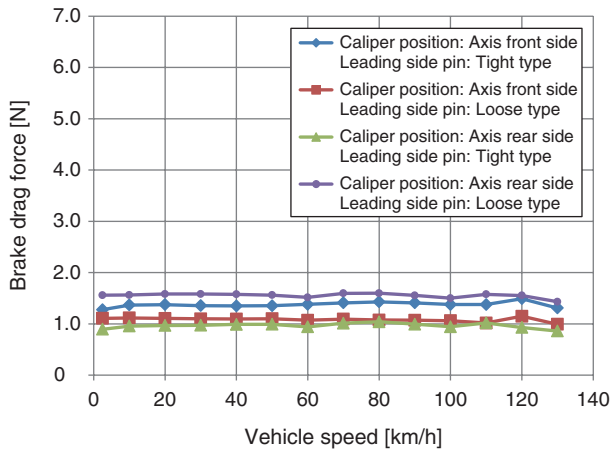


Fig. 20 Brake drag force by caliper position and pin type

5. Proposal of Drag Stabilization and Reduction Methods

In order to realize methods for brake drag stabilization and reduction, design-related guidelines regarding the main causes of drag are formulated as follows.

First, a pad return spring structure was configured. When doing so, it is necessary to configure the inner pad inclination relative to the disk so that it maintains clearance between them while open on the leading side in order not to generate vacuum pressure between the pad and the disk. In order to maintain this inclination in a stable manner, observe the tendency shown in Fig. 21, which presents an organized view of parameter study results on the pad return spring load balance. The pad return load on the leading side of the pad return spring must be greater than on the trailing side. The shaded portion of Fig. 21 is an approximate guide to the target area of configuration. The colors in the graph are blue to indicate a relatively low drag value category of 2 N or less, which is stable; orange to indicate drag from 2 N or greater to 4 N or less; and red to indicate large drag figures at that level or higher. In order to stabilize the pad return load, a coating of grease should be applied between the retainer and pad.

In order to prevent the inner pad and disk from coming into contact while the vehicle is in C/D mode, it is also necessary to assure that the value of the piston R/B with the caliper body deformation subtracted is maintained. The shaded area in Fig. 22 indicates the target for specifications.

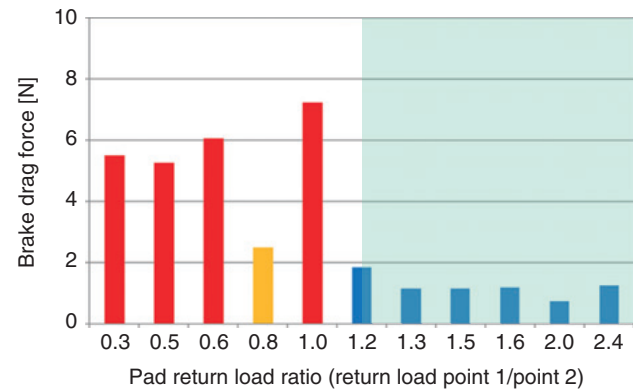


Fig. 21 Design target of pad return load balance

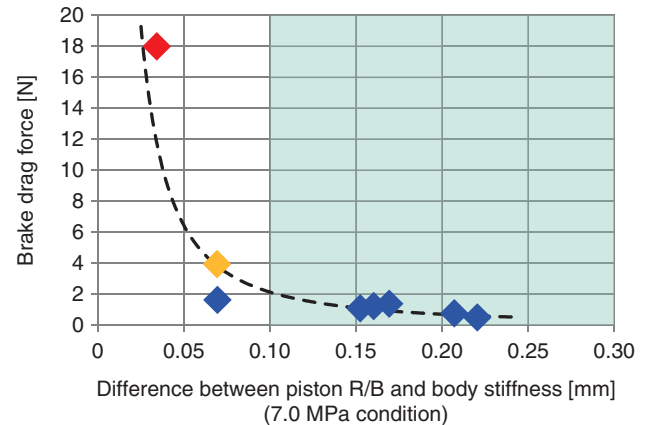


Fig. 22 Design target of piston R/B and body deformation

6. Conclusion

The mechanism of brake drag during C/D mode was clarified in bench testing. When operating in this mode, the brake disk is subject to heat deformation during the process of repeated brake operation. The disk temperature drops during the subsequent drag value measurement process, and its shape returns from its heat deformed state. It was found that drag occurs at this time when the disk and the inner pad come into contact. It was also found that when the inclination of the inner pad relative to the disk surface leaves a smaller clearance between them on the leading side than on the trailing side, vacuum pressure is generated between the inner pad and the disk. This causes the inner pad to be drawn toward the disk, where they come into contact. It was found that this can trigger the phenomenon of suddenly increasing drag values. A parameter study of the caliper was also conducted, and yielded the following findings that contribute to the stabilization and reduction of drag values.

- (1) The pad return load setting on the leading side and on the trailing side of the pad return spring should have the load on the leading side higher than on the trailing side, and the inclination of the inner pad with respect to the disk should be such that clearance between them is retained on the leading side.
- (2) The remainder when caliper body deformation is subtracted from piston R/B serves as a reference value that should sufficiently be maintained.
- (3) The brake disk should be designed to reduce heat deformation of the disk.

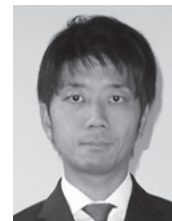
References

- (1) SAE J2263: Road Load Measurement Using Onboard Anemometry and Coastdown Techniques (2008)
- (2) SAE J2264: Chassis Dynamometer Simulation of Road Load Using Coastdown Techniques (2014)
- (3) Gamo, Y., Suzuki, S., Kumemura, Y.: Development of the CLZ type Disk Brake Design Technology, TOKICO review, Vol. 43, No.1, p. 6-13 (2001) (in Japanese)
- (4) Gamo, Y., Ishii, H., Suzuki T., Kumemura, Y.: Development of the Technology for Reducing Caliper Drag Torque, TOKICO review, Vol. 42, No.1, p. 20-26 (2001) (in Japanese)
- (5) Nakai, K., Nobata, Y., Saito, N.: Dhisuku no Netsuhenkei Teigen niyoru Burekijada Teigenshuho no Kaihatsu, MAE technical report, No.14, p. 27-34 (2005) (in Japanese)

■ Author ■



Yasushi KOBAYASHI



Yuta HIGUCHI



Naoki NAKAMURA