NVH Simulation Technology for Disc Brake Calipers

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OVERVIEW: A comfortable automobile is one in which both noise and vibration are suppressed, and in which the conditions are satisfied for a smooth ride. This is why NVH, which represents these conditions, has come to be used as an evaluation standard for automobile comfort. Noises that occur in disc brakes for automobiles come in a number of different categories, each with different causes. Of these categories, the noises referred to as "brake squeals" and the vibrations referred to as "brake judders" are caused by a complicated phenomenon whose reduction improves the value of automobiles on the market. Hitachi applies NVH analysis technology to make improvements through both experimental trials and simulations.

INTRODUCTION

IN recent years, although the dynamic performance of automobiles has improved radically, demand has been growing at the same time for both comfort and silence. This need for further improvements includes a reduction in the noise and vibration that can occasionally occur during braking, and which can give car occupants a feeling of discomfort.

Independent organizations have been conducting vehicle evaluations to determine customer satisfaction levels recently, including the surveys of J. D. Power and Associates in the USA and the automotive magazine "auto, motor und sport" in Germany. Poor evaluation results in these surveys are a major problem because they lead to reduced vehicle sales while causing damage to the automobile manufacturer's brand image.

Since brake noise and vibration are among the items evaluated in these surveys, further improvement is needed in these areas as well. The phenomena that cause these problems are complicated, and clarifying the mechanisms involved is a vital part of the improvement process.

This document describes the efforts of Hitachi with respect to technologies for analyzing NVH (noise, vibration, and harshness, whereby "harshness" refers to a lack of smoothness in the ride) caused by automobile disc brakes.

DISC BRAKE NOISE AND VIBRATION

Noises and vibrations in an automobile's disc brakes are a phenomenon caused by the discs coming into contact with friction material, resulting in frictional vibrations that generate resonance in the brake components or vehicle body. "Brake squeals" and "brake judders" are typical examples of these noises and vibrations, accounting for approximately 70% of complaints.

TABLE 1. Typical Types of Abnormal Noises Caused by Disc Brakes
Abnormal brake noises occur under a wide range of conditions, and have different tones as well. Countermeasures must match the specific phenomenon in question.

Abnormal noise type	Noise example	Condition for occurrence (sound frequency)	Countermeasure
Groaning noise	Goo noise	Sound generated in the instant that the foot is taken off the brake pedal in a state such as when an AT car starts moving downhill, or when swing-over occurs while the car is halted (50 to 300 Hz)	· Appropriate selection and tuning of pad material
Humming noise	B noise Boo noise Moaning noise	Sound that occurs when the car starts moving very slowly after the brake is released, or during turning; this "boon" sound is particularly likely to occur in a rear disc (200 to 400 Hz)	· Reduction in drag · Increased underbody rigidity
Rumbling noise	Roaring noise Grinding noise	Roaring sounds such as "goh, goh-goh" that occur during the reduction of speed caused by ordinary braking; caused by concave flexing in the surface of friction material, maturation of transferred film to the rotor surface and other factors (50 to 300 Hz)	· Pad material change · Pad slit adjustment
Clonking noise	Clonking noise	Sound occurring during ordinary braking at low speeds (in particular during reverse driving after stopping, for instance), when the pad hits the torque member's torque support hole	Optimization of the tangential direction gap between pad and torque member
Rattle noise	Pin rattling noise Pad rattling noise	Rattling noise that occurs when metal parts hit each other during rough road driving (in the non-braking driving state), such as a pin and pinhole, or a pad and pad guide	· Pad clearance optimization · Clearance optimization inside pinhole, etc.

AT: automatic transmission

A brake squeal is a noise between 1 and 16 kHz that is generated directly by the brakes. Since this is a phenomenon that is difficult to reproduce, and which varies depending on factors such as temperature, humidity, speed, and the force of the foot pressing down on the pedal, countermeasures are difficult to develop.

Steering vibrations, vehicle body vibrations, and brake pedal vibrations can also be caused by gradual braking (deceleration between 1.5 and 3 m/s^2) during high-speed driving. These vibration phenomena that occur during braking are referred to with the generic term "brake judder." Brake judders, which are one form of low-frequency vibration, occur when brake vibration during braking travels from underbody parts into the steering, resulting in sympathetic vibration. Sometimes this can cause the vehicle body to resonate to the extent that the vehicle body itself vibrates, making a groaning noise throughout the entire vehicle body. The main sources of this phenomenon are steady vibration of the vehicle body system by the braking system and the resonance characteristics of the frictional vibration with the vehicle body. The inputted exciting forces include fluctuation in the braking torque, which is caused by disc deformation and uneven thickness.

Types of noises and vibrations related to automobile brakes other than brake squeals and brake judders are shown in Table 1.

Hitachi is working on measures to prevent the wide variety of NVH problems related to brakes.

SQUEAL NOISES AND NOISE ANALYSIS TECHNOLOGY

This section discusses the causes of brake squeals and the technology used to analyze them.

In general, friction brakes use sliding caused by dry friction to generate a braking force, which always results in tiny fluctuations in the frictional force. This can then resonate with the parts around the lining material, further amplifying the fluctuations in frictional force and causing parts with a relatively large surface area to vibrate, which in turn vibrates the air and generates a noise. This is referred to as "self-exciting vibration," and brake squeals are a typical example of the phenomenon.

Contributing factors behind brake squeals include the physical characteristics of friction material such as friction coefficient speed dependencies, thermal factors caused by disc thermal deformation and so on, and structural factors caused by issues such as the form of brake vibrations. All of these factors mutually influence each other. The current mainstream of brake squeal analysis focuses on structural factors, mainly the resonance characteristics of brake components, and many research projects are being undertaken today.[(1) - (3)]

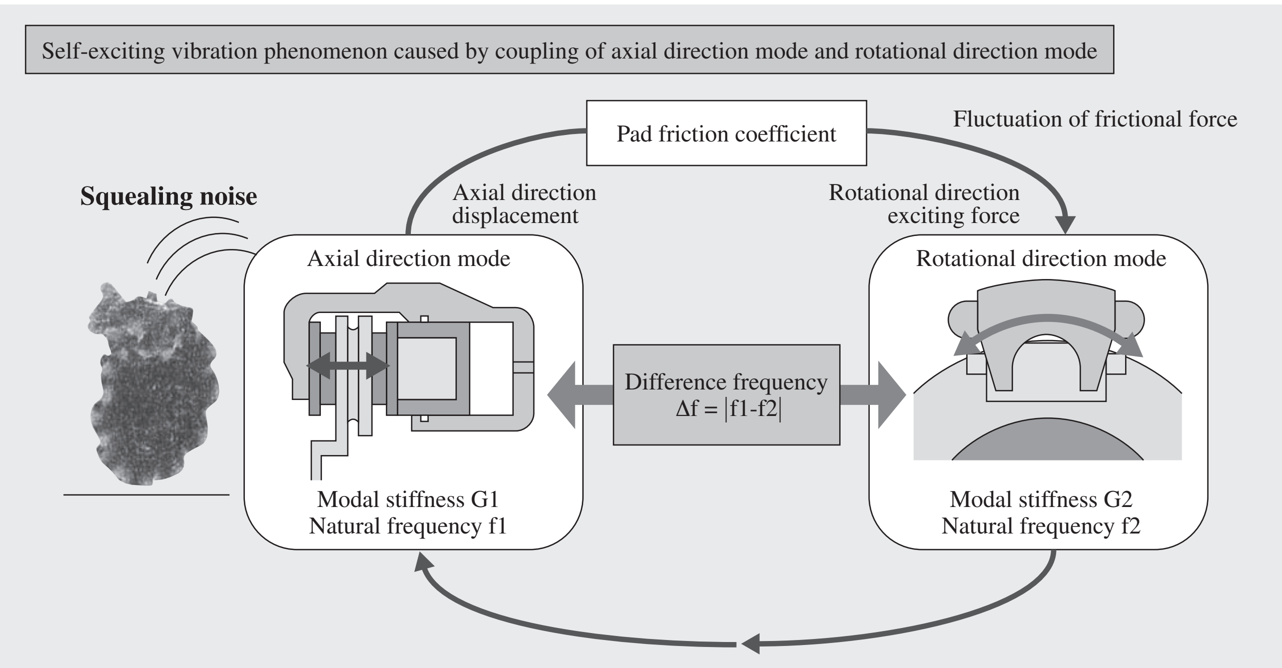

Fig. 1—Mechanism for Brake Squeals Caused by Mode Coupling.
When vibration modes with different directional components are coupled due to frictional forces, a self-exciting vibrational loop is formed that generates a brake squeal.

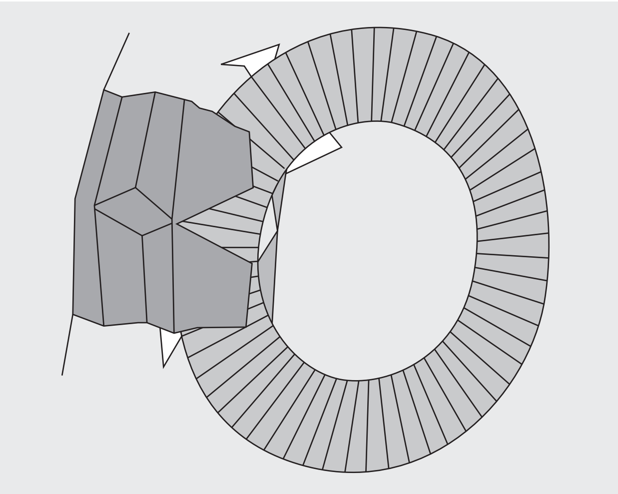

Fig. 2—Brake Operating Deflection Shape.
This visualization of the measurements of vibrations in each part of the brake is used to identify the sites where countermeasures are needed.

Squeals often occur under special conditions, such as on cold days or when humidity is high. The frequency of occurrence is not very high under normal conditions.

This is why squeals are a difficult phenomenon to reproduce, whether in an actual vehicle or in a laboratory, and the vibrational form during the occurrence of actual squeals (referred to as the "operating deflection shape") is not easy to measure. Therefore, during the development of actual products, we work to reduce squealing by clarifying areas to improve through both operating deflection shape measurements and experimental modal analysis of vibrations. Although a number of factors are thought to be behind the generation of squeals, this discussion covers squeals that are caused by mode coupling.

This phenomenon generates squeals when the axial direction mode and rotational direction mode excited by frictional vibrations become coupled and the amplitude of the frictional force intensifies further, thereby resulting in a self-exciting vibration that excites the vibration mode (see Fig. 1).

Therefore, in order to reduce squeals, it is important to grasp the vibration modes in the axial and rotational directions that influence squealing in order to lower the vibration level, and to increase the natural frequency differential of the rotational and axial directions in order to prevent these resonance vibrations from coupling.

As a countermeasure against these types of brake squeals in actual products, the aforementioned brake operating deflection shape is measured to identify the site with high vibration amplitude that requires dynamic stiffness, and improvements are then made (see Fig. 2).

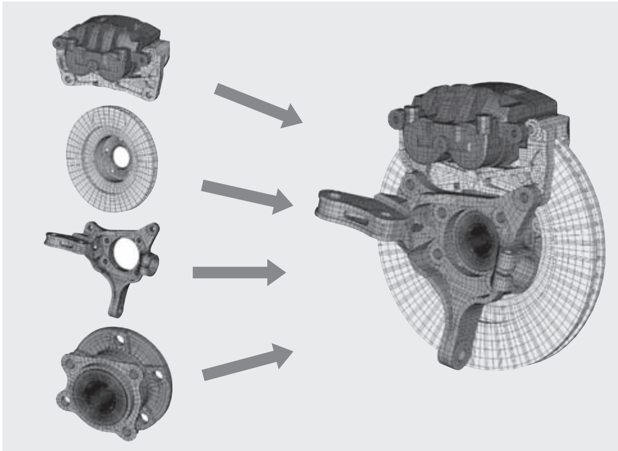

Fig. 3—Disc Brake Finite Element Model.
The finite element method is used to perform a vibration simulation using a model with multiple degrees of freedom.

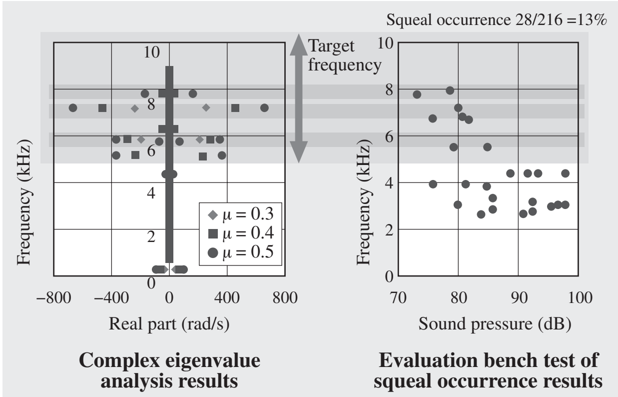

Fig. 4—Example of Brake Squeal Analysis through Complex Eigenvalue Analysis.
The unstable vibrations acquired by analysis correlate to the evaluation of actual products, and can therefore be used to predict brake squeals caused by mode coupling in advance.

For further performance improvements and reductions in development man-hours and cost, complex eigenvalue analysis is used with a finite element method. This enables the use of brake squeal prediction technology to improve the countermeasures used to prevent vibration modes that lead to self-exciting vibration (see Figs. 3 and 4).

The real parts of complex eigenvalues acquired through analysis represent the instability of vibrations, such that the larger the value, the higher the probability that a brake squeal will occur. For this reason, part design is aimed at reducing this instability.[4]

BRAKE JUDDERS AND JUDDER ANALYSIS TECHNOLOGY

There are two basic types of brake judder.

The first type is referred to as "high-temperature judder." The discs grow hot during braking, and this thermal expansion causes a rippling deformation to occur in the rotational direction, leading to braking torque fluctuation and the judder.

The second type is referred to as "low-temperature judder," or "time degradation judder." This occurs off-brake (during ordinary driving, with the brake not applied) when the brake's dragging causes disc wear, resulting in uneven thickness (fluctuation in thickness of several micrometers can occur after driving over a distance of 10,000 to 20,000 km). Braking in this state will cause the braking torque to fluctuate, generating judder.

Countermeasures against high-temperature judder involve rotor stiffness and increased heat capacity, and the current mainstream in judder analysis focuses on the latter type, low-temperature judder. In particular, work is focusing on explaining the mechanism through which the disc thickness becomes uneven due to the drag phenomenon (see Fig. 5).

When the thickest part of a disc that has become uneven passes the brake pads, the piston and cylinder claw are pressed back, increasing brake fluid pressure. Likewise, when the thinnest part of the disc passes the brake pads, brake fluid pressure decreases. These pressure fluctuations during braking result in brake torque fluctuations, which in turn become an exciting force that causes coupled vibration in the steering and suspension, resulting in the judder phenomenon.

Hitachi uses simulation technology in its efforts to reduce brake judders by preventing rotor thickness from becoming uneven while off-brake (see Fig. 6).

The behavior of brake parts while off-brake is measured in order to clarify which parts have a great deal of influence on drag, so that countermeasures can be produced to reduce drag and keep pad surface pressure down.[(5), (6)]

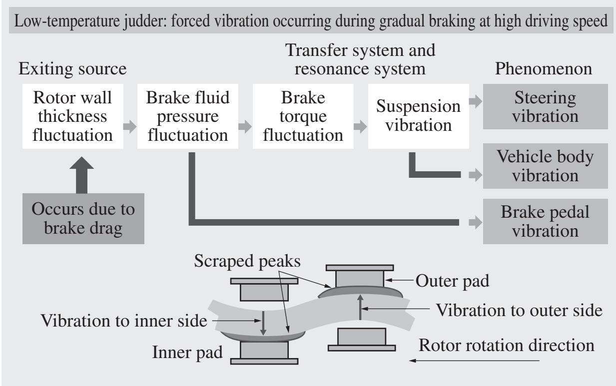

Fig. 5—Mechanism for Low-Temperature Judder.
Fluid pressure fluctuations occur due to unevenness in discs, and torque fluctuations propagate to steering and the vehicle body.

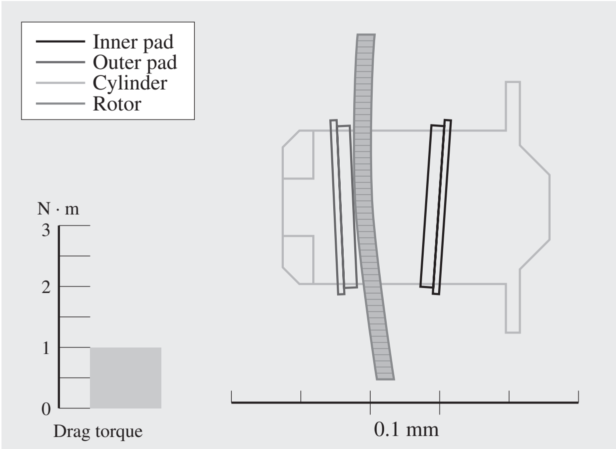

Fig. 6—Brake Drag Analysis.
The torque generated by contact between disc and pad is calculated during off-brake time.

BRAKE NVH ANALYSIS TECHNOLOGY OUTLOOK

Brake-related vibration noises occur in a variety of different environments and under a variety of different usage conditions. In particular, factors such as rate of occurrence and sound frequency will vary depending on conditions such as brake temperature, fluid pressure, pad properties, state of wear, and driver input. This is why even the current analysis technology has not yet reached the stage whereby noises can be completely prevented.

In addition, in recent years, there has been a demand for weight reductions and restrictions in the use of certain friction materials from an environmental perspective, and a demand for a larger friction coefficient and a reduced brake operational force from the perspective of brake efficiency improvement. Since these demands all cause fundamental increases in vibration noise, it is becoming difficult to achieve effective improvements by simply applying existing methods.

Although the current NVH analysis technology does have a track record of improving a large number of brake vibration noise problems, there is a need for advancement in order to meet the aforementioned demands, and even problems that occur infrequently must be made predictable during desk work. From this perspective, Hitachi is working to develop high-precision analysis technology focusing on the following points, with a wider range of application:

(1) Analysis technology that considers fluctuations in the friction state

(2) Analysis technology that covers a wide range of braking conditions
(3) Improvements in the precision of correlation between experiment and analysis

A focus on these points will make it possible to predict noises and vibrations under conditions that could not be considered previously. Furthermore, by applying these points to product design, it will be possible to construct robust disc brake products that do not elicit vibration noises during a wide range of usage conditions.

CONCLUSIONS

This document discussed Hitachi's efforts in the area of NVH analysis technology for use in automotive disc brakes.

Experimental analysis technology and noise and vibration simulation technology is now an indispensable part of the analysis-driven design of disc brakes.

The trend in recent automobiles is moving towards an increase in particularly low-noise vehicle types such as hybrid vehicles and electric vehicles, and so the demand for improvements in brake NVH is expected to continue growing even stronger.

Hitachi plans to continue with its efforts in the area of low-noise and low-vibration brake development, achieving advances in vibration and noise reduction technologies with the goal of making further improvements in automobile comfort.

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