

Analysis of Vibration Behavior of Full Vehicle during Brake Judder

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ABSTRACT

A variety of components and systems in a vehicle are involved in brake judder. Up to the present, many papers have explored the roles of the brake and suspension in judder, but quite few have taken up the analysis of the vibration behavior of transfer systems, such as the steering system, subframe and body, from a viewpoint of their impact to brake judder.

This study employed bench tests to reproduce driving conditions. In order to analyze the transfer system, vibration of the entire vehicle was measured and behavior analysis was performed by visualization of vibration phenomena. Much was learned about the vibration behavior of the steering system, subframe and body, and the basic mechanism of brake judder involving the entire vehicle was proposed.

In addition, the influential factors in the transfer system were identified, and the contribution of each was analyzed.

1. Introduction

As examples of research into brake judder carried out to date, many reports of research on the brakes, which constitute the source of vibration, and on the suspension, which constitutes a resonance system^{(1) - (6)} exist. However, there are few papers covering the analysis of the effect of the steering system, sub frame and body, which constitute the vibration transfer system.

In order to analyze the mechanism of vibration of the entire vehicle including the transfer system, using an experimental analysis method, it is necessary to measure the vibration behavior of each part of the vehicle. In some cases the total number of measurement points reaches 100. For this reason, data measurement at all necessary points in a track test in a single operation requires large-scale measuring equipment, so the test itself is difficult to carry out. On the other hand, when using a method that involves dividing measurements into several sets, it is challenging to stably generate the same vibration phenomenon during repeated tests, and

thus the accuracy of the analysis becomes an issue.

There are cases in which a chassis dynamometer is used in bench tests, however, in these cases the excitation source remains torque variation, which depends upon the characteristics of the friction material of the brake. Consequently, it is not possible to obtain a significant modification from the viewpoint of stably generating a vibration phenomenon.

To address these issues, a bench test method with high reproducibility permitting the same vibration phenomenon to be generated during repeated tests, as well in contrast to a track test, and enabling high quality vibration data to be acquired, was studied in this research.

Next, to obtain a grasp of the basic mechanism of brake judder, this test method was used and all of the measured data for each test analyzed together, enabling the vibration mode of the entire vehicle to be visualized and behavior analysis performed.

This report details the identification of the influential factors affecting vibration and a contribution analysis of each of these factors from the results of vehicle behavior analysis and track testing.

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2. Bench Test

2.1. Selection of the Test System

In the study of the bench test method, a comparison of the following two types of test system was carried out.

- (1) Chassis dynamometer (Fig. 1)
- (2) Tire patch exciters (hereafter called TPE. See Fig. 2)

The former is used in general brake tests and is well known. The latter (TPE) is test system made by MTS, which uses two shakers and air bearings to shake the left and right front wheels of the vehicle.



Fig. 1 Chassis dynamometer

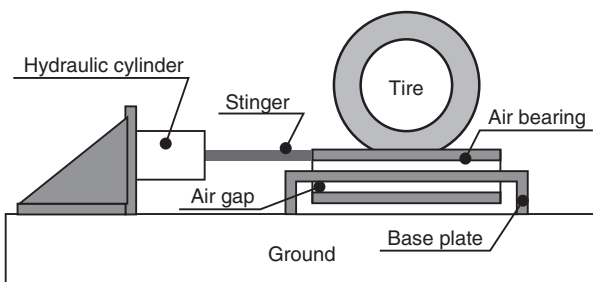


Fig. 2 Tire Patch Exciters

In a test using a chassis dynamometer, it is possible to use a test method that directly substitutes a bench test for a track test, so the reproducibility of the vibration phenomenon with respect to the track test is very high. However, as in the case of the track test, the excitation source is the brake torque variation, which depends on the friction material characteristics, so the same issues remain with regards to stably generating the same vibration phenomenon in repeated tests.

Also, because it is necessary to use the brakes for vibration excitation, waiting time is needed to allow the brake components to cool down between one measurement and the next. This results in long test times for multiple point measurements or under conditions where repeated testing is required to compensate for poor stability of the generated phenomenon. Consequently, in product development where reduction of development time and elimination of prototype vehicles are demanded, the use of a dynamometer is considered unsuitable as a study method due to the poor time efficiency of the work involved.

To solve these tasks, a study of the TPE was carried out next. By using an excitation method employing a shaker to stabilize the input of the excitation source, it is possible to generate the vibration phenomenon repeatedly and stably. In addition, there is no need to carry out braking using brakes, so there is no need to wait for the brake components to cool down between one measurement and the next.

For the above reasons, a TPE was selected as the test system in this research.

2.2. TPE Bench Test Method

As the input condition for securing reproducibility of the vibration phenomenon with respect to a track test, it is necessary to control the shaker so that typical brake torque variation is reproduced when a disk rotor of non-uniform thickness is installed. Figure 3 shows the torque variation of an average brake obtained from a single dynamometer test. The torque variation characteristics are converted into a longitudinal force at the point where the tire

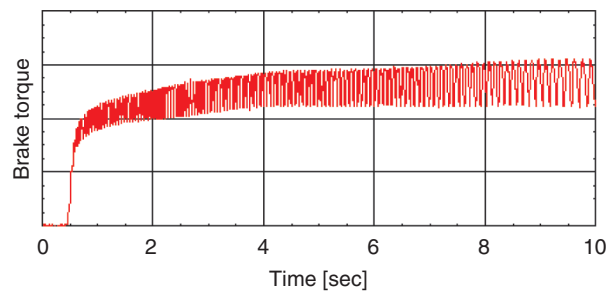


Fig. 3 Measurement data: brake torque variation (single dynamometer)

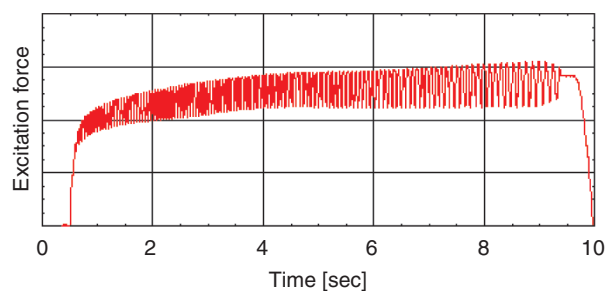


Fig. 4 Excitation force: Tire Patch Exciters

touches the ground, to become the input data. The results of reproducing this force with a TPE are shown in Fig. 4. There is good agreement between both sets of results, indicating that the reproducibility is adequate.

Figure 5 shows the measured results of the acceleration of the steering rotational vibration (tangential direction component at the outer radius of the steering wheel) obtained from 10 repetitions of a track test, compared with the measured results obtained from a bench test using a TPE. Here, the change of amplitude over time is represented in graphical form by plotting only the peak value for each wavelength (Fig. 6). By comparing these two results, it can be seen that steering rotational vibration during the bench test matches the average value for the track tests, and the change of vibration over time is reproduced well.

It was therefore judged that, as a result of the above, the test method established had high reproducibility with respect to the track test, and was able to stably generate the same vibration phenomenon on a bench test. This method is used to perform multiple point measurements for the purpose of performing vehicle behavior analysis.

3. Basic Mechanism

An adequate number of measurement points were used for each component and each system, in order to create an operational deflection shape during the occurrence of the vibration phenomenon. Figures 7 and 8 show the respective operational deflection shapes in time history, created from the data at these measurement points. As a result of analyzing these operational deflection shapes, the basic mechanism of brake judder occurrence, shown in Fig. 9, was understood.

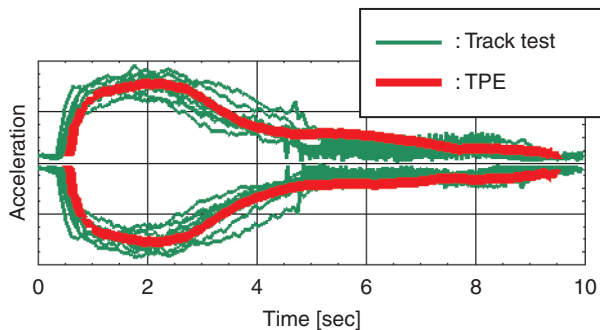


Fig. 5 Rotational acceleration: steering wheel comparison between track test and TPE

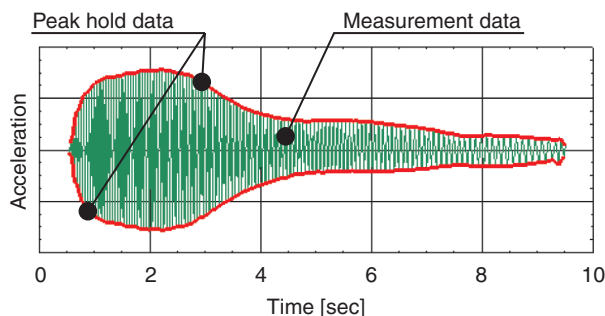


Fig. 6 Steering wheel acceleration: peak hold data

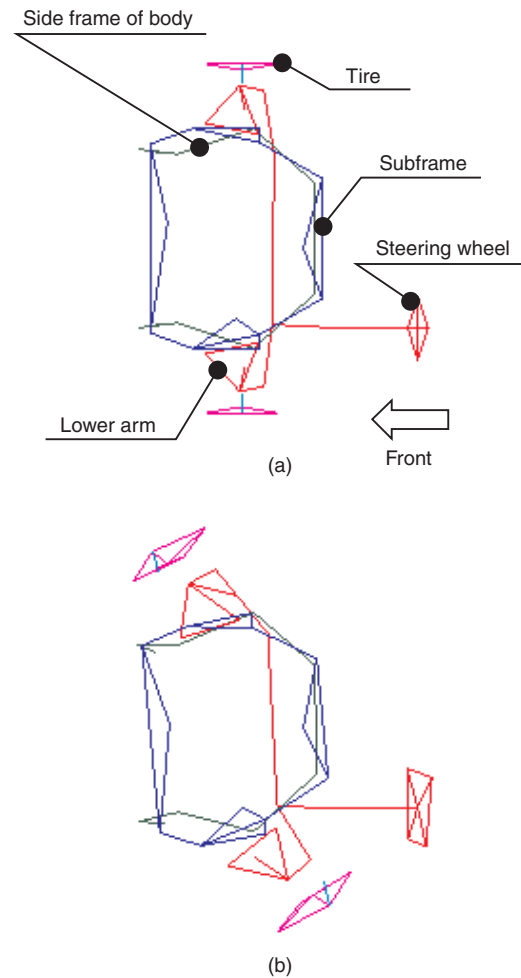


Fig. 7 Operational deflection shape at TPE (suspension, steering, subframe and side frame of body)

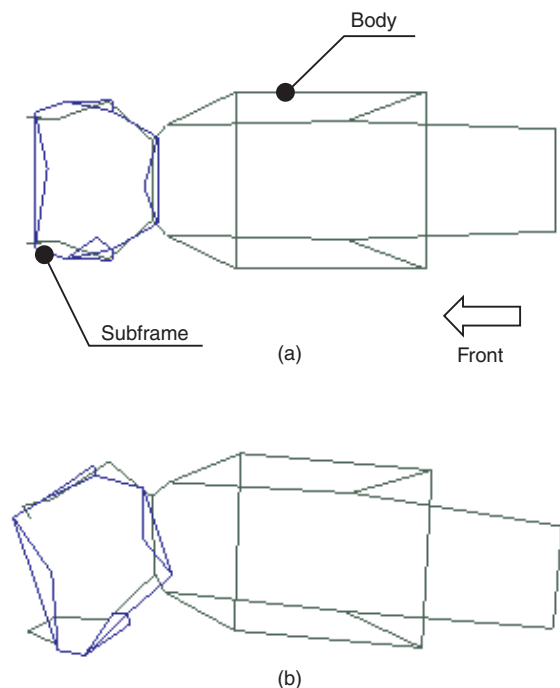


Fig. 8 Operational deflection shape at TPE (subframe and body)

The transfer path (1) of vibration, shown on the left side of the figure, is the conventionally known transfer path in which longitudinal vibration from the suspension - a main cause of brake judder - becomes rotational vibration about the king pin axis, and passes through the tie rod to become steering vibration.

In contrast, transfer paths of vibration (2) and (3) shown at center and the right side of the figure are the transfer paths related to vibration of the sub frame and body, newly clarified in this research. As a result of the generation of longitudinal vibration of the suspension, the sub frame that supports the suspension is excited in the lateral direction at the lower arm bushing point, and in the lateral and longitudinal directions at the compliance bushing point. As a result, the sub frame vibrates in the lateral direction while rotating slightly around the vertical axis of the vehicle. Concurrently, the housing of the gearbox mounted on the sub frame also vibrates in the lateral direction, more or less integrally with the sub frame, generating a relative displacement with respect to the rack, which becomes the rotational vibration of the steering. This is transfer path (2).

Vibration of the sub frame is also transmitted to the body, which supports it, and the body itself also vibrates in the lateral direction while undergoing lateral bending at the front from the cabin. This is transfer path (3), and is the mechanism of body vibration when brake judder occurs.

As a result of performing the abovementioned vehicle behavior analysis using multiple point analysis, it was determined that there are two transfer paths through which rotational vibration of the steering occurs, and it was possible to help elucidate the mechanism by which body vibration occurred.

In addition, vehicle behavior analysis was likewise carried out for multiple additional vehicles employing different types of front

suspensions, and the abovementioned basic mechanism of brake judder was observed to be the same in each case.

4. Influencing Factors in the Transfer System

4.1. Study of Modification of the Sub frame and Body

When studying proposals for modification to the vehicle, it is possible to establish guidelines for such proposals by focusing attention on areas where major deformation and vibration occur, according to the operational deflection shapes in Figs.7 and 8. Here, attention was focused on the deformation of the mount bushing of the sub frame and the lateral bending deformation of the front end of the body.

In order to minimize deformation of the sub frame mounting part, a reinforcement patch equivalent to a rigid mount was added, and to suppress lateral bending deformation of the front end of the body, a reinforcement patch was added to each member of the body. When the shape of the reinforcement patch was being studied, the finite element method (FEM) was used to analyze each member's sensitivity to lateral bending deformation, and the reinforcement locations were thus determined. Figure 10 shows the results of comparing the stiffness levels on the body without the sub frame, with and without this reinforcement. It can be seen that lateral bending deformation has been reduced by about 17% due to the body reinforcement.

Regarding vibration transfer to the body, it is clear from the results of this vehicle behavior analysis that vibration is transmitted from the lower arm mounting point on the sub frame. Consequently, in order to evaluate change in stiffness level related to brake judder due to the reinforcement, a comparison of static deformation at the

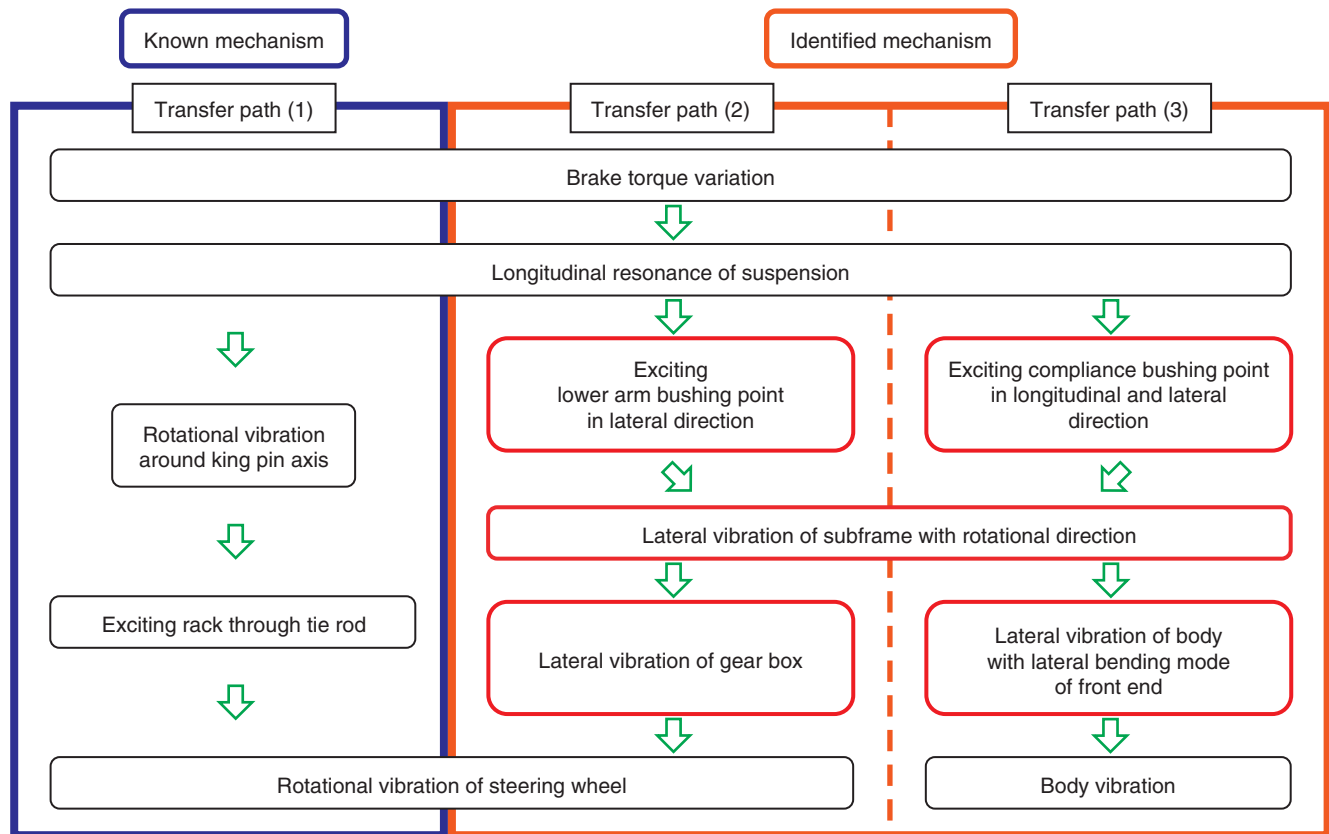


Fig. 9 Basic mechanism of brake judder

lower arm bushing point was performed. The results are shown in Fig. 11. For specifications under which a reinforcement patch was applied to the body alone, the stiffness of the lower arm bushing point remained almost unchanged. In contrast, for specifications under which a reinforcement patch was added to the sub frame mounting part as well as to the body, the deformation was reduced by about 64%. From this it can be confirmed that in the case where a vehicle has a sub frame mounted via a mount bushing, the increase in stiffness of the lower arm bushing point due to the body reinforcement alone is low.

As a result of performing track tests to evaluate these two modification proposals, it was confirmed that whereas no meaningful difference was found for body reinforcement alone, an enhancement of about 20% was obtained for specifications under which both the body and sub frame mounting parts were reinforced, which matches the case results of studying stiffness of the lower arm bushing part.

4.2. Effect of the Steering System

The steering system is the final path of vibration transfer containing the steering wheel from which the driver directly detects judder, and thus performs an important role. However, the vibration phenomenon is reduced mainly by increasing sliding resistance of the rack in the steering gearbox such as damper and friction, and there have been almost no cases of research into other factors carried out to date. In this research, attention was focused on the column shaft, and a study of its effect was carried out.

The column shaft comprising the steering system normally uses yoke joints due to the vehicle layout (Fig. 12). The shafts connected

by these joints intersect at an arbitrary angle, causing the transfer characteristics to vary based on rotational position. Furthermore, the influence of friction at the yoke joints also changes along with the rotational position, so the total friction characteristics of the column shaft also change.

In order to check the way in which these characteristics affect brake judder, a track test of the yoke joint phase differences of the column shaft in a neutral position of the steering was carried out. Figure 13 shows the yoke joint phases at which measurements were performed, the rotational transfer rate fluctuations at each position, and the characteristics of rotational friction. Figure 14 shows a comparison of the steering rotational vibration results for each of these positions. In the case of this testing, it was confirmed that the maximum difference obtained was about 30%. Consequently, it was deemed necessary to take adequate consideration of these characteristics when performing brake judder studies.

In the case of steering systems with a tilt and telescopic mechanism, the shaft intersection angle changes along with the position of the steering wheel, which in turn causes the rotational transfer rate to fluctuate and the frictional characteristics to change. It is therefore important to select a yoke joint phase that is not readily affected by these factors.

4.3. Degree of Contribution of Influencing Factors

Through actual cases of the abovementioned analysis, it was possible to help elucidate the contribution of influencing factors in the various components of the transfer system, including the steering system, sub frame and body. Accordingly, the influencing factors (including the steering damper, which has been conventionally used to suppress rotational vibration) have been set out below, in decreasing order of contribution.

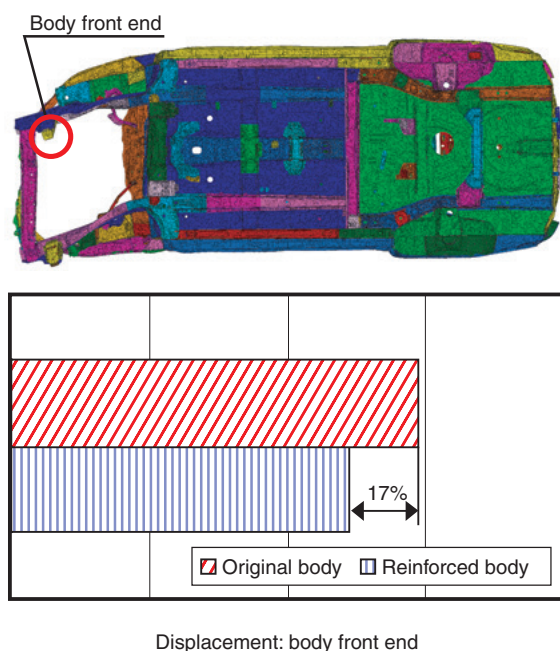


Fig. 10 Body stiffness level without subframe

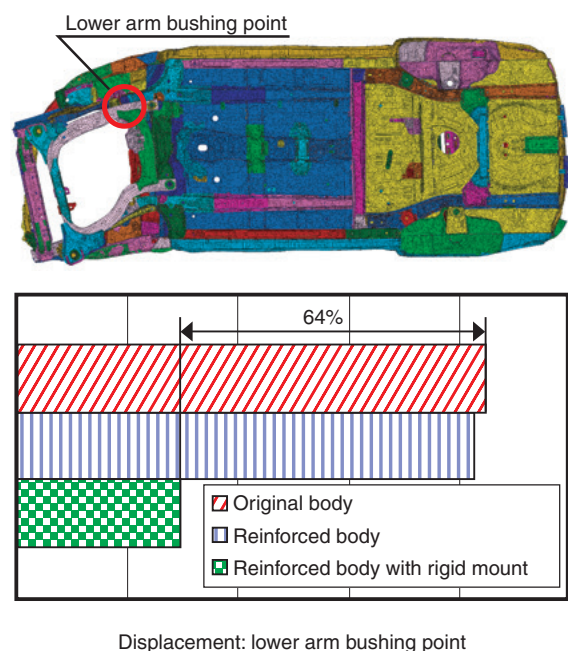


Fig. 11 Body stiffness level with subframe

- (1) Yoke joint phase
- (2) Steering damper characteristics
- (3) Sub frame mount

By thus extracting the factors influencing the transfer system and analyzing their contribution, it was possible to help identify the points of modification related to brake judder from various components and systems of the overall vehicle, including the excitation source and resonance system.

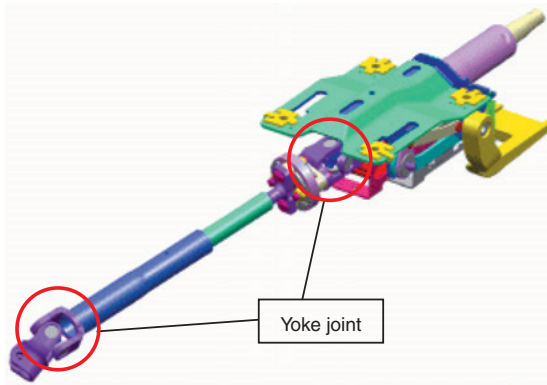


Fig. 12 Yoke joint: column shaft

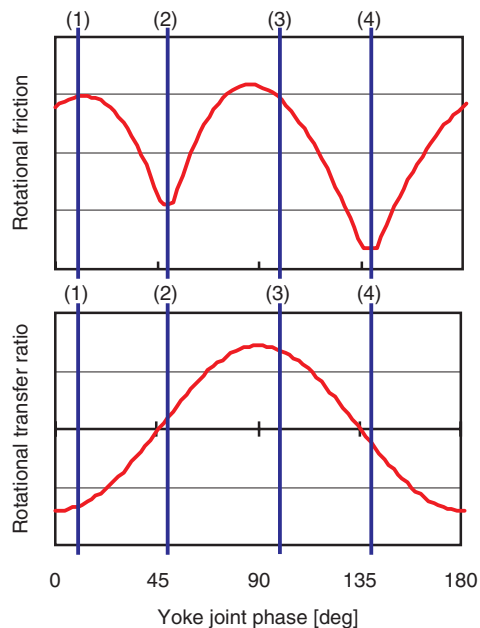


Fig. 13 Characteristics of column shaft

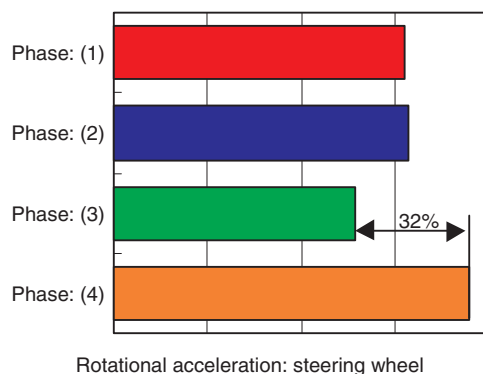


Fig. 14 Result of track test

5. Conclusions

By using a bench testing system to excite vibration, it was possible to perform vehicle behavior analysis concerning brake judder, and also to analyze the component contributions to the transfer system, from which the following conclusions have been obtained.

- (1) As a result of using a bench test employing TPE, it was possible to establish a test method that had high reproducibility, could stably generate the vibration phenomenon, and permitted vehicle behavior analysis to be performed efficiently.
- (2) As a result of visualizing the vibration behavior when brake judder occurred, it was possible to obtain a grasp of the basic mechanism of vibration transfer from the brake to the steering wheel and body.
- (3) It was found that the transmission characteristics changed greatly along with the rotational vibration of the steering wheel, depending on the yoke joint phase and the tilt and telescopic positions of the column shaft in a neutral steering position.
- (4) It was possible to help elucidate modifications related to brake judder in relevant components and systems of the overall vehicle, including the excitation source and resonance system, by extracting each factor in the steering system and also the transfer systems in the sub frame and body, and analyzing the respective contributions.

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