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〈Original Paper〉

Test and Diagnostics Methods for Judder Vibration of the Brake System

자동차 제동장치의 져더 진동 측정 및 진단 방법

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Key Words : Judder Vibration(져더 진동), Disc Thickness Variation(디스크 두께 변화, DTV), Order Tracking Analysis(차수분석), Brake System(제동장치)

ABSTRACT

Brake judder(or cold judder) caused by the disc thickness variation(DTV) is investigated experimentally. This cold judder is often perceived by steering wheel vibration, brake pedal pulsation, and vehicle body vibration. In this paper, how the DTV profile affects the vibration characteristics of vehicle body is shown by order tracking analysis(OTA) and operational vibration analysis(OVA). The tri-axial vibrations are measured at the knuckle, lower arm, and the body side of the lower arm. Also, measured are the wheel speed and the detail DTV profile. The interpretations of OTA results in three directions of tested vehicle indicate the relative importance in the contribution of the run-out and the DTV to the judder vibration. Also, the OVA results show the prominent vibration amplitude of the lower arm in the direction of the vehicle movement, in which the second order of wheel speed is dominant. These results could be used to diagnose the judder problem and to establish the correction methods.

요 약

디스크 두께 변화(DTV)에 의해 야기되는 져더현상은 일반적으로 차체진동, 브레이크 페달 떨림, 그리고 스티어링 휠의 떨림에 의해 감지된다. 이번 연구에서는, 차수분석 및 Operational Vibration Analysis(OVA)를 통해 차체진동이 DTV profile에 의해 어떻게 영향을 받는지를 중점적으로 조사하였다. 진동 측정위치는 knuckle, lower arm, lower arm 연결 차체부위 이고, 져더 발생 DTV profile도 실측하였다. 시험 분석 결과, DTV는 져더현상에 차수별 상대적인 방향 기여도를 나타내며 특히 디스크 회전 2차 성분은 차량진행 방향으로의 lower arm 진동을 현저하게 야기시키는 것으로 나타났다. 이러한 시험 및 분석 기술은 져더 현상을 진단하고 문제를 개선하는데 유효하리라고 예측된다.

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1. Introduction

Brake induced vibrations of passenger cars have been well known among vehicle NVH (Noise Vibration & Harshness) issues, and now become more important factors on vehicle system designs such as suspension system, steering system and body. Due to low frequency vibration characteristics ranging 10~30 Hz, brake judder is differentiated from other brake NVH problems such as creep groan or squeals. Also, brake judder is different from other NVH issues since it is more likely vibration related phenomenon than noise. Thus, the judder can be perceived by steering wheel vibration, brake pedal pulsation, and vehicle body vibration on light brakings from high to low speed. Like other braking problems, judder has resulted in complaints and claims against automobile manufacturers, and therefore, more extensive analysis on judder phenomenon and adequate diagnosis tool are still required.

Although judder is known to be a first order with respect to wheel speed, it is also related with the second and higher order excitations. There are two main sources causing judder. One is the imbalance of wheel system and the other is brake torque variations(BTV). When the imbalance of wheel system becomes prominent during braking, it induces noticeable vehicle shake(1). However, a large part of brake judder is coming from the brake torque variations(1). The BTV can create two different types of judder depending on whether the BTV is induced by either thermal background or mechanical background. The judder with thermal background called "hot judder" occurs when high speeds associated with high braking forces that lead to very high temperature in the disc rotor and thus to distortion of the disc rotor. This judder is more likely related with the number of hot spots, and thus higher orders of wheel rotations such as 6th order and 12th order(2). On the other hand, the judder with mechanical background called "cold judder" is related with uneven wear of disc rotor side faces and this leads to the disc thickness variations(DTV) and thus to brake torque variations. In this study, the latter type of judder is focused on.

In view of braking system development, the studies on relationship between judder and disc thickness variations are more concerned and the solutions for preventing the occurrence of judder would be found eventually in reducing DTV since cold judder is caused by BTV due to DTV. Understanding this relationship should be accompanied by the vehicle evaluations on judder vibrations, and there are two ways to choose : either subjective or objective evaluation. The evaluation on cold judder has mostly been performed subjectively since the judder can be perceived by a driver via brake pedal, steering wheel, or vehicle body. The diagram in Fig. 1 describes the possible paths of transfer mechanism during judder.

Although subjective evaluations are good enough to check whether the judder exists or not, the subjective tests have limitations such as requiring longer period of testing time, not easy maintaining the repeatability, and lacking quantitative data about judder mechanism. Moreover, Haigh et al(3) revealed that the subjective evaluations are not easily referred to measured data related to judder. They showed

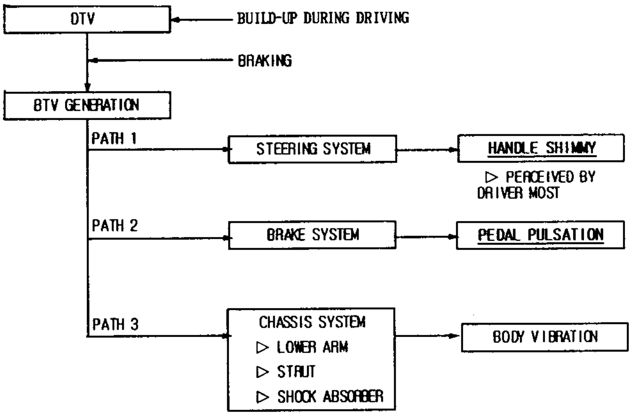

Fig. 1 Judder vibration transfer mechanism

that the amount of disc thickness variations is not linearly related with subjective judder evaluation although the judder is generated by the disc thickness variations. Since subjective evaluations do not provide sufficient information on judder mechanism, it is important to perform additional objective evaluations through the proper testing methods.

The conventional testing methods to get objective evaluations usually provide two types of data. One is for checking the levels of judder vibrations on the developing vehicle and the other is for comparing the measured levels to those of other vehicles relatively or target values absolutely. For the measuring places, the chassis components as used in subjective evaluations are preferred to correlate objective data with subjective data. So far, the most popular way is collecting vibration data from steering wheel since it is known to be the most sensitive vibrating spot during judder(2,5,6). Thus, most analysis has been executed based on measured data at the steering wheel. However, this method is too much oriented for detecting the occurrence of judder along the test conditions and the relative differences in vehicles. In order to reveal and clarify the inside of judder mechanism and thus lead to trouble shootings and preventing problems, the more detailed analysis and studies on judder with different sensor locations should be proceeded.

Gassman et al(2) have explained the transfer mechanism from wheel knuckle to steering wheel during judder by using transfer functions with directly measured vibrations and disc thickness variations. Abdelhamid(6) used transfer function and vehicle sensitivity for judder analysis on knuckle to steering wheel vibrations. Lately, using sensitivity analysis, Kim et al(4) pointed out more specific and sensitive components on judder mechanism. They showed that the stiffness of lower control arm bushings attached to the body affected the judder vibrations greatly. It would be very informative on trouble shootings and preventing problems if additional information is available on top of their work. For example, how the specific chassis components behave during judder, how excitations through knuckle to lower arm would trigger the judder, what order of wheel rotation is mostly related to judder motion at the body, etc.

In this study, it is focused on adding information on motions of judder related chassis components along the transfer paths and thus, the proper testing method is introduced, and discussed are the results of the case study

2. Case study : operational motion of lower arm during judder

2.1 Measurements

The selected vehicle for judder test was a used(80,000 km) mid-sized passenger car and the brake judder was measured on the proving ground at Samsung motors. The tested vehicle is front loading drive with Mcpherson front suspension and approximated 900 kg curb weight.

Parameters of the measurements were the

Table 1 Locations and numbers for sensors

Ch	Sensor	Location	Direction
1	acc	front knuckle	fore-aft (x)
2	acc	front knuckle	lateral (y)
3	acc	front knuckle	up-down (z)
4	acc	lower arm(front)	fore-aft (x)
5	acc	lower arm(front)	lateral (y)
6	acc	lower arm(front)	up-down (z)
7	acc	lower arm(rear)	fore-aft (x)
8	acc	lower arm(rear)	lateral (y)
9	acc	lower arm(rear)	up-down (z)
10	acc	body	fore-aft (x)
11	acc	body	lateral (y)
12	acc	body	up-down (z)
13	wheel rotation	ABS	-

wheel speed and vibrations at the front knuckle and lower arm. As shown in Table 1, the locations and numbers of accelerometers were on front wheel knuckle(in all 3 directions), lower arm rear bushing (in all 3 directions), lower arm front bushing(in all 3 directions), and the body side connected with the lower arm(in all 3 directions). Figure 2 describes the sensor locations for measurements. The wheel speed was measured by the front wheel ABS signal. All measurements were carried out with light braking(0.2 g) from high to low speed. The data collections were repeated three times to check the repeatability on judder. Also, the DTV profile of the front brake disc rotor was measured.

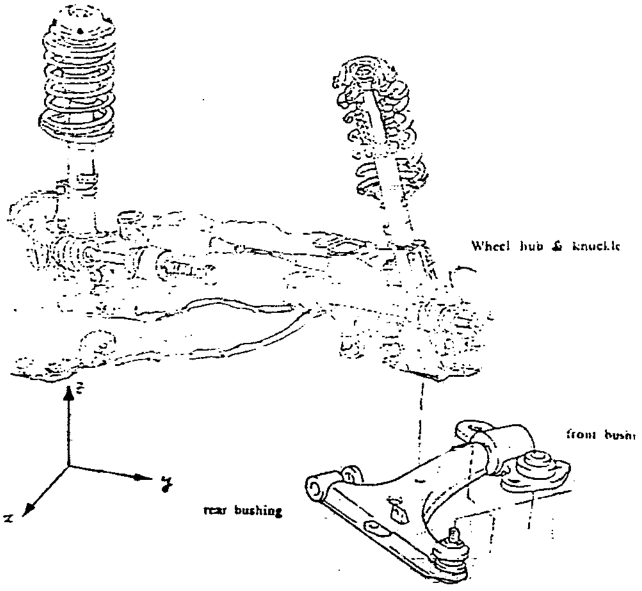

Fig. 2 Locations of accelerometers (x : fore aft movement direction, y : lateral movement direction, z : up down movement direction)

2.2 Data Analysis

After collecting data of 13 channels using a digital audio recorder simultaneously, data analysis was performed using a commercial software package, LMS CADA-X. The analysis was designed into three parts, frequency analysis, order tracking analysis(OTA) and operational vibration analysis(OVA). First, a general frequency analysis was executed to check whether there is a dominant resonance in chassis components. Secondly, the color map from the order tracking analysis was used to see how the

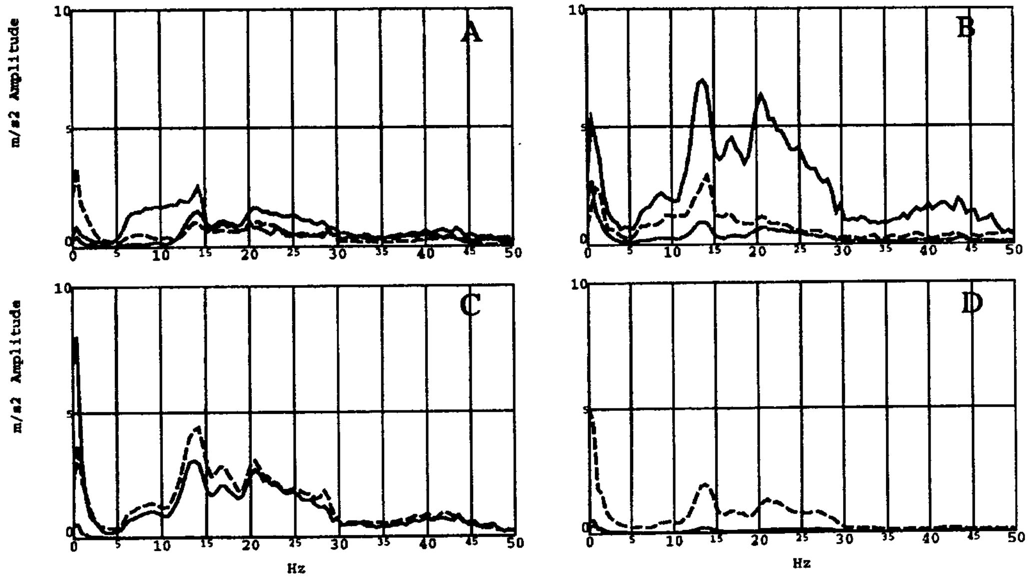

Fig. 3 Locations of accelerometers (x : fore aft movement direction, y : lateral movement direction, z : up down movement direction)

vibrations were affected along the wheel rotations in frequency, so that the directional dependency on vibrations could be visible. Also, the distinguished orders at the specific component were investigated to find their contributions to the overall vibrations. Finally, the highly contributing orders were investigated at each location so that the operating modes of the knuckle, the low arm bushing and the body side connected to the low arm bushing were visualized according to the studied orders.

2.3 Results

Figure 3 shows averaged frequency spectrum along the measured chassis components through 370~720 rpm. As shown in Fig. 3, it is clear that the chassis components and wheel undergo a resonance around 14 Hz.

Figure 4 A, B and C show OTA results of directional judder vibrations at the wheel knuckle. The vibrations rely on the harmonic orders of wheel rotations, but the corresponding order was not same for all directions. The second order was dominant in the x and z directions and the first order was manifest in the y direction. Similar results were obtained at the other measured points along the presumed transfer path.

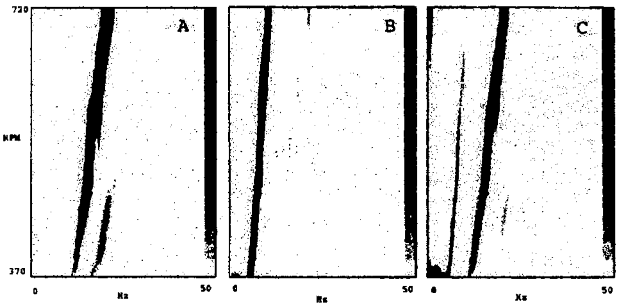

Fig. 4 Order tracking analysis results of each direction at the wheel knuckle (A : x direction, B : y direction, C : z direction)

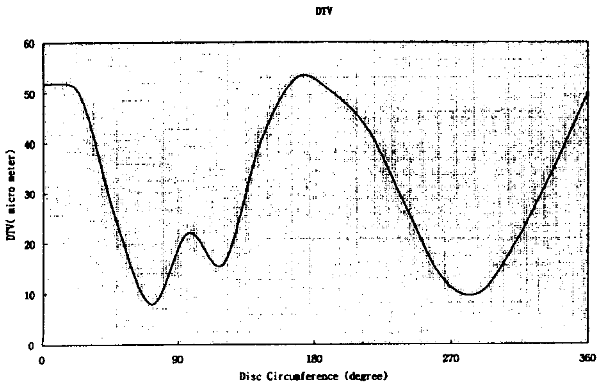

Fig. 5 DTV profile of front disc

The profile of disc thickness variations is plotted in Fig. 5 which described the second order along the circumference of the disc rotor.

Also, Fig. 6 describes the contributions of main orders to overall vibrations in the different directions at the wheel knuckle. The vibrations

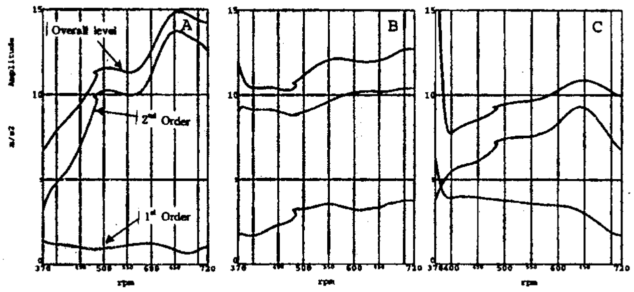

Fig. 6 Order contribution to overall level at the wheel knuckle in each direction (A : x direction, B : y direction, C : z direction)

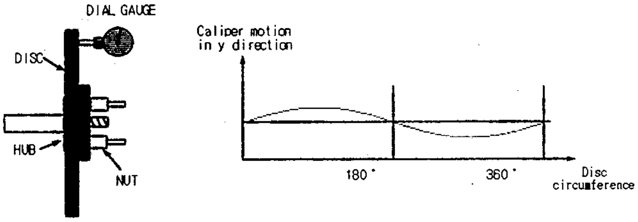

Fig. 7-A The first order excitation due to run-out

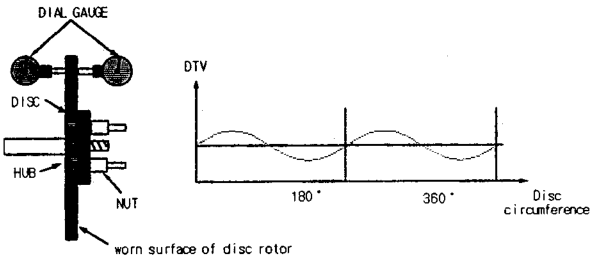

Fig. 7-B The second order excitation due to DTV

along the second order were prominent. The results at different components are not exactly same as those of wheel knuckle. The first order contribution is decreased and the second order remains in overall contributions as a dominant source.

Figure 7-A simulates the first order excitation due to run-out and Fig. 7-B describes the second order excitation due to disc thickness variations. The measured DTV profile of front disc rotor in Fig. 5 is very close to the results of simulation.

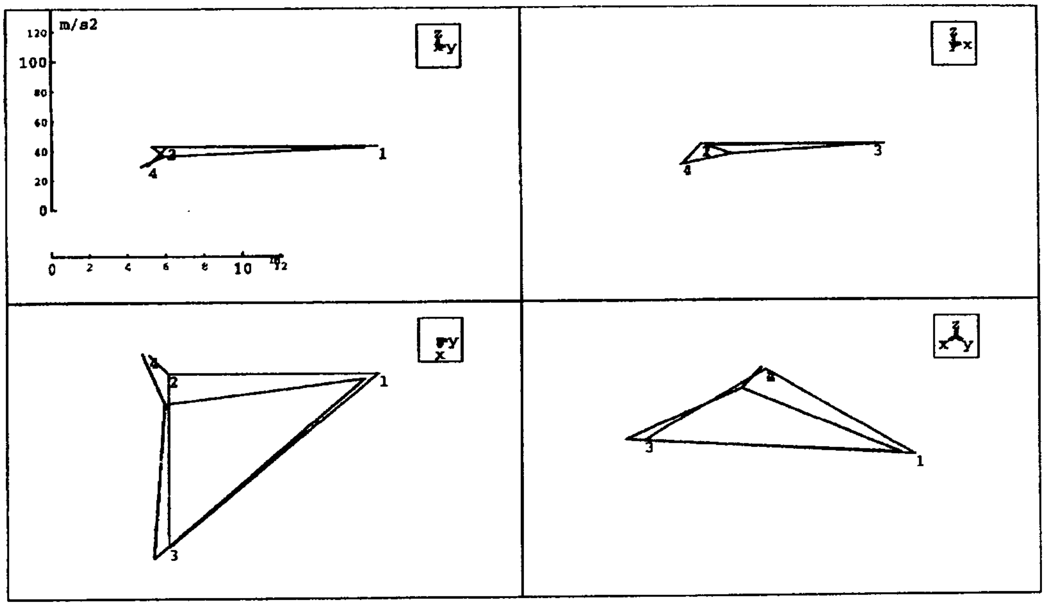

Fig. 8 Running modes of body side at the first order (point 1 : Wheel Knuckle, 2 : Front bushing of lower arm, 3 : Rear bushing of lower arm, 4 : Body)

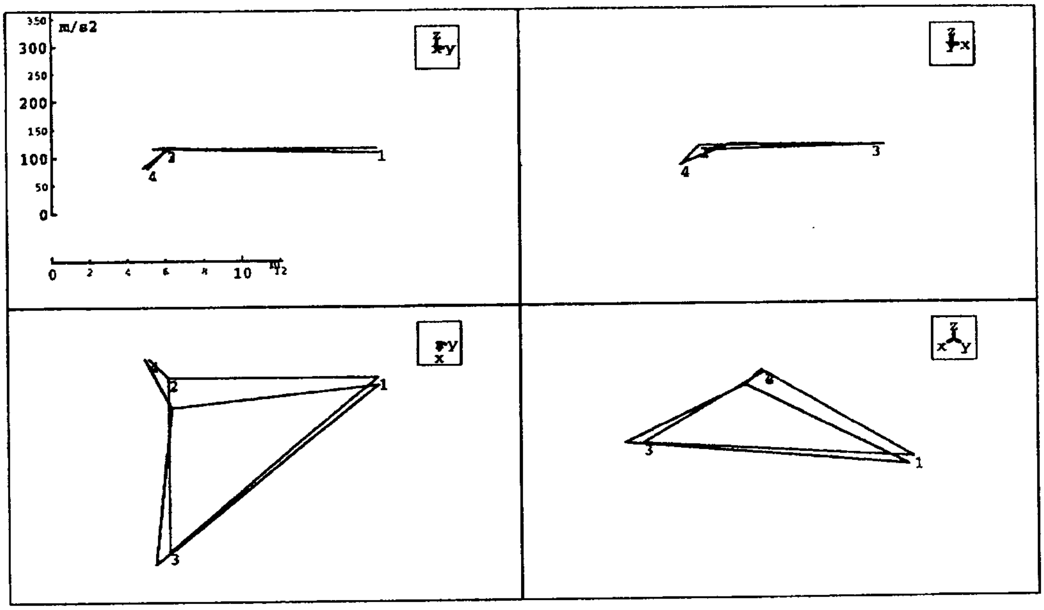

Fig. 9 Running modes of body side at the second order (point 1 : Wheel Knuckle, 2 : Front bushing of lower arm, 3 : Rear bushing of lower arm, 4 : Body)

The OVA results are visualized in Fig. 8 and 9. The running modes of the rear and front bushings of lower arm show the same directional dependency at the first and second order, but the knuckle did not show the same directional dependency at each order. In Fig. 8, the vibrations at knuckle are strong in the *y* direction but the vibrations at lower arm bushings are substantial in the *x* direction. In Fig. 9, dominant vibrations of both lower arm bushings and knuckle are all in the *x* direction.

2.4 Discussion

In this case study, it is shown that the judder vibrations are dependent upon the harmonic orders of wheel rotations. The excitation that is triggered by the wheel rotations has propagated from wheel to body through lower arm. The second orders in Fig. 4 & 7 match well with the measured profile of disc rotor shown in Fig. 5. Thus, it is well explained that the judder is very much related with DTV. Although the order dependent vibrations were apparent on every measured chassis component, there are considerable findings that every order is not affecting judder vibrations and the same order is not dominant in every direction of measured points. Moreover, there are differences in order contributions to overall level according to the directions. At the knuckle, the vibrations along the first order were only prominent in the *y* direction. On the other hand, the second order was *x* direction dependent and true for the *z* direction. In further analysis at different points that is not shown here, the second order was dominant in all directions except for *z* direction of the front bushing where the first order was conditionally dominant.

Since the first order contribution to judder vibration was not consistent at measured points, it can be assumed that the first order is not strongly correlated with judder vibration in the body side. On the other hand, the vibrations along the second order always existed in the *x* direction of all measured components. As shown in Fig. 7, the plausible candidate excitation affecting cold judder is either a second order or a first order. As simulated in Fig. 7A, the run-out during braking would mostly affect the caliper motion so that the first order would be dominant in the *y* direction if the case is right. However, the measured DTV profile from the tested vehicle was the second order. Namely, the DTV profile generated the second order in the *x* direction (torque variation direction) due to the uneven wear on the sides of disc rotor as shown in Fig. 7B. Therefore, it could be inferred that the second order dependent vibrations were transmitted to other components and thus lead body vibrations during judder in this case study.

Although it is clear that the second order due to DTV is the apparent source for judder on the body side, it was examined further to see how the second order affects the chassis components using OVA. In addition to the investigation on order contributions, the OVA results clearly showed the dominant movement in the *x* direction at lower arm. As far as the removals of severe judder vibrations are concerned, there are two ways to consider. One is eliminating the source of judder and the other is reducing the level of vibrations transmitted along the transfer path. The replacement of the disc rotor to eliminate the judder source is not as simple as it sounds. The reason is that the DTV, source of judder, exists eventually as long as the vehicle is deriven. That means, there is a moment to decide to replace the disc rotor due to DTV. However the amount of DTV is not linearly related to judder and thus hard to define the DTV judder criteria on replacing disc rotors. Therefore, the reducing in vibration level is preferred as an alternative. The OVA results can be recommended as one of promising trouble shootings. As shown running modes in Fig. 8 & 9, the lower arm is flexible enough to be easily affected by the excitations in the *x* direction due to DTV. As a possible solution for reducing the level of judder in this case study, the front bushing stiffness of lower arm should be increased in the x direction.

3. Conclusion

The cold judder induced by the disc thickness variations was investigated. Vibration data measured along the transfer path to body were mainly focused in this case study although the judder vibrations can be detected subjectively via steering wheel, brake pedal, and body of testing vehicle. Once the subjective evaluation was done, measurements on three axial vibrations at the knuckle, lower arm, and body side were performed for further analysis and understanding on judder mechanism. The order tracking analysis revealed how the DTV profile and wheel rotations related to judder vibrations along the transfer path. It shows that judder vibrations are known to be order dependent, and the dominant order at each chassis component is also dependent on the specific direction along the transfer path. Moreover, operational vibration analysis indicated that at the lower arm bushing the second order dominated the judder vibrations specially in the direction of fore aft movement. These results could be used to diagnose the judder problem and to establish the methods on troubleshooting.

Acknowledgments

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