技術解説

The Power of Oil – Influence of Shock Absorber Oil on Vehicle Ride and Handling Performance

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Abstract

When the suspension deforms, damping force is generated as the piston of the shock absorber moves, but a time difference occurs before the large hydraulic damping force rises. At the same time the frictional force in the shock absorber is playing an important role in generating effective damping force against deformation of the suspension, the generated force itself is small but its response is high. The frictional force in the shock absorber occurs in reciprocating motion in various speed ranges from amplitude of less than one millimeter to larger amplitudes, its behavior changes dynamically and is non-linear. Recent studies have revealed that controlling the friction is more important than reducing it for improvement of the performance. Because of this we have investigated the dynamic friction characteristics of shock absorber oil and sliding parts, by the means of an own developed device that can measure the speed dependence of friction force in reciprocating motion with high accuracy.

The result of our analysis shows that friction dissipates energy at a speed level of 0.002m/s where hydraulic dissipation is not working yet. By knowing this phenomenon, we have developed different kind of oil types in order to generate various dynamic friction characteristics.

The influence of our developed oil types on the ride and handling performance was tested and analyzed in different vehicles. Subjective assessments and objective measurement show the vehicle performance improvement, which can be generated by using more advanced oil types.

Keywords: shock absorber, damping force, dynamic friction, riding comfort, stability, vertical dynamics

1 Introduction

The damping force of the shock absorbers (SAs) is one of the elements making up the characteristics of the suspension system, and it mainly affects vehicle stability and ride comfort. In recent years, vehicles experience smaller fluctuations in the vertical direction even at high speed as road conditions have improved. Therefore, SAs are often operated at high frequencies with small amplitude, where the direction of SA motion is frequently reversed and the SAs are mainly operated at the low speed.

SA generates damping force by hydraulic oil passing through valves attached to a piston, SA responsiveness is affected by elastic deformation of oil (oil column rigidity)[1] especially at the point where the direction of SAs is reversed. There are new technologies that adjust hydraulic force, for example, a hydraulic valve structure[2] and an electronically controlled SA[3] aiming for generating appropriate damping force according to the road surface conditions by changing hydraulic force. However, these technologies are limited in terms of their ability to improve the damping force when the direction of motion is reversed because of deformation of oil. The current situation calls for SAs that improve ride comfort and safety (stability, steering response) when driving on good roads as moved very low speed of SAs.

Experience with on-vehicle subjective evaluation of SA performance indicates that ride feeling on good roads can vary greatly with hydraulic oil difference. In this paper, we focus on effect of hydraulic oil on vehicle ride and handling. And then, we developed our own hydraulic oil to adjust the damping force in the very low speed range where direction of motion reverses, in order to clarify the factors that influence the change in feeling.

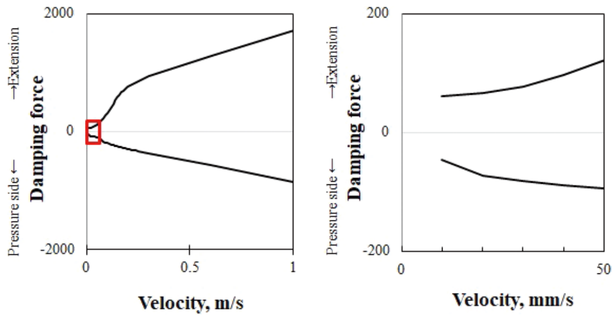

Fig. 1 Damping force - velocity characteristics line diagram

2 Shock Absorber Design

2.1 Conventional damping force measurement method and its problems

A conventional indicator of the performance of SA is shown in Fig. 1. The right figure is a magnified one of the surrouded area by the red square in the left figure. Here, the performance of the SA is evaluated by a plotting the peak damping force generated by the SA versus stroke speed, which is called "damping force - speed characteristic line diagram". Generally, it does not show speeds of 10mm/s or below. It is a quasi-static characteristics and not suitable for the evaluation of dynamic performance. Hence, in order to evaluate the SA performance on good roads, we believed that it was necessary to evaluate the dynamic characteristics from the time of reversing the moving direction to the very low speed region, which has not been noticed in the conventional performance evaluation.

2.2 Fluid resistance and friction force in damping force

Fig. 2 shows the structure and damping force components of a twin-tube-type SA. As shown in the figure, hydraulic force is generated by the pressure change as hydraulic oil passes through the valves[4], and friction force is generated from the oil seal, the rod guide, and the piston band. The damping force of SAs is the sum of the hydraulic force and the frictional force. We believe that in the very low speed region, a region which has not yet been extensively studied, the hydraulic force would have a smaller impact on the damping force, while the friction force, which has nonlinear characteristics, would have a greater impact [Fig. 3].

In order to understand the relative contribution of hydraulic force and frictional force to the total damping force, we investigated the damping force-speed characteristics. The measurement experiments were conducted as follows.

First, we prepared a valve-less SA by removing valves in order to generate no hydraulic force, and we measured the damping force which now consisted only the friction force. This enables us

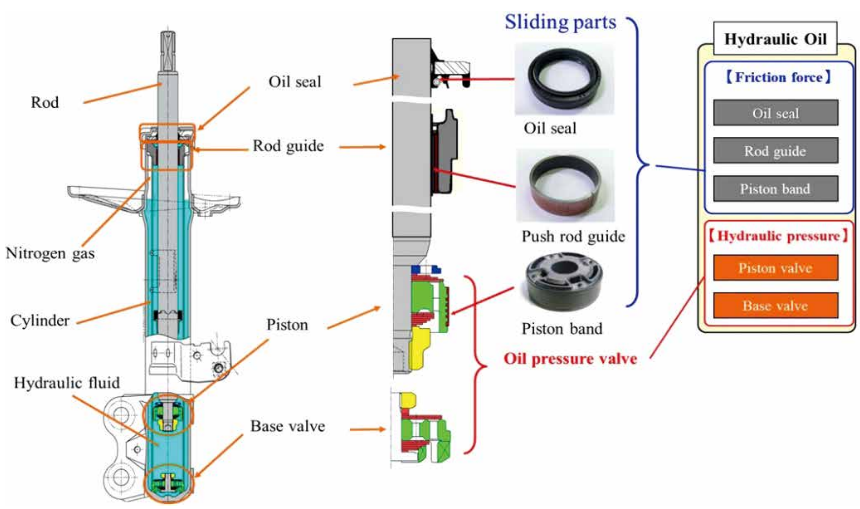

Fig. 2 Twin-tube-type shock absorber structure and damping force component

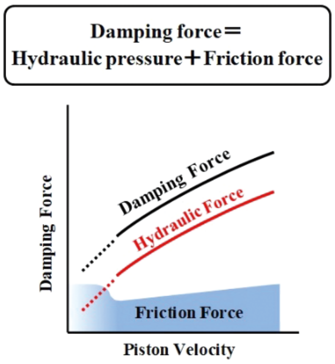

Fig. 3 Relationship between piston speed and damping force

to determine the speed characteristic of the hydraulic force from the difference between the damping force - speed characteristic of a normal SA and that of the valve-less SA. Fig. 4 shows the changes in the proportion of hydraulic force and the frictional force in the damping force as a function of the piston speed. The figure shows that the proportion of friction force is the highest in the very low speed region where the piston speed is 30mm/s or less.

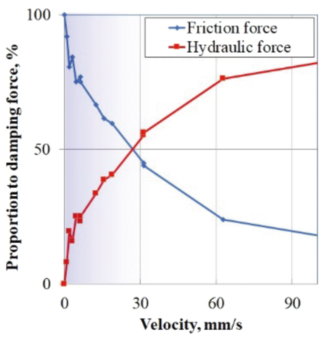

Fig. 4 Speed dependency of load ratio of hydraulic pressure and friction force in damping force

Next, we analyzed the behavior of the shock absorber on the test course in order to determine their functionality on a good road. In the experiment, we drove a passenger car with a displacement of 1.8L at 60km/h on a test course that reproduced the uneven road surface equivalent to a good road on a national highway. During the experiment, a displacement sensor was mounted in parallel to the SA, as shown in Fig. 5, and the displacement was measured at 2-kHz intervals, to calculate the frequency distribution of the stroke speed and the displacement. Fig. 6 shows the frequency distribution of the SA speed and Fig. 7 shows the displacement distribution from the neutral position of the SA. We found that for at least 50% of the time on a typical good road, the displacement of the SA would be less than or equal to ± 1.5mm from the stroke center. We also found that for 50% or more of the time, the piston speed was less than or equal to ± 30mm/s, and the most frequent speed was less than or equal to ± 10mm/s.

In these low-speed and low-amplitude regions, little hydraulic force is generated, and the damping force consists mostly of the friction force. In other words, on good roads, the damping force of SAs is largely dominated by the friction force.

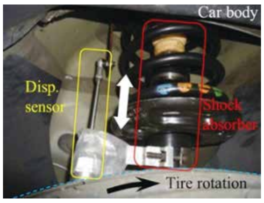

Fig. 5 External view of suspension displacement behavior measurement during actual vehicle running

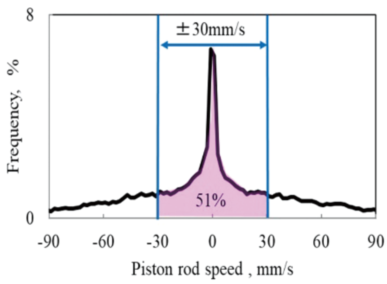

Fig. 6 Frequency distribution of piston speed

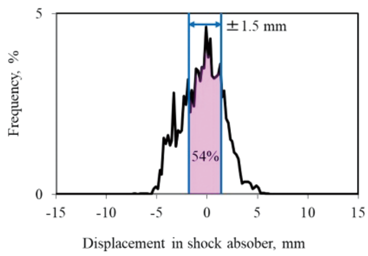

Fig. 7 Frequency distribution of displacement from neutral position

2. 3 Evaluation methods and problems in the low-speed operation region

In order to evaluate the dynamic characteristics of the damping force, we use a plotting the force generated by SA versus stroke speed when the

SA is operated at a constant frequency and amplitude, as shown in Fig. 8. The low-speed region around the zero point (surrounded by the red square) in Fig. 8 is magnified in Fig. 9.

Damping force has hysteresis due to the compressibility of the hydraulic oil[1], that works in the form of oil column rigidity as shown in Fig. 10, and in the very-low-speed zone starting at the zero line where the direction of motion reverses, the damping force of SAs is in the direction of acceleration. We believe that the SA response can be improved by reducing this zone.

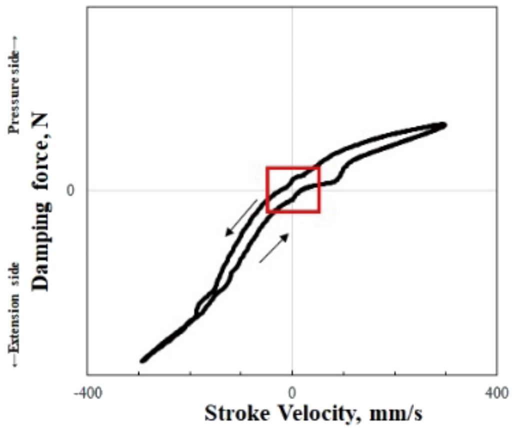

Fig. 8　F-V characteristics

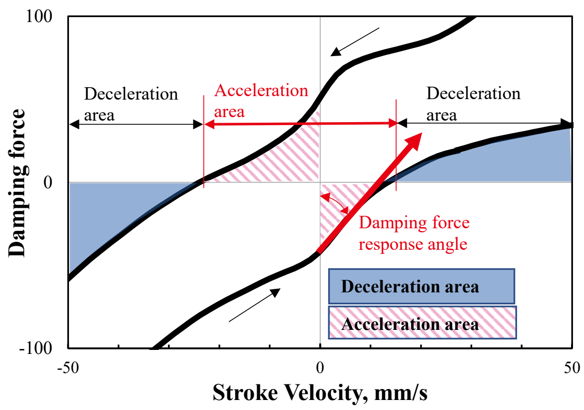

Fig. 9　F-V characteristic around the zero point

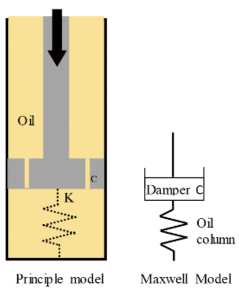

Fig. 10　Influence of oil column stiffness characteristics

Friction adjustment using hydraulic oil has been studied in order to improve SA responsiveness, but the response which was observed as the gradient around zero point and the magnitude of the friction force are simultaneously changed as shown in Fig. 11 in order to avoid the occurrence of stick-slip. However, when this method is used, the responsiveness is improved, but at the same time, the ride comfort is deteriorated, and this trade-off characteristics have not been improved. Therefore, we thought that we can improve the responsiveness of SAs without deteriorating the ride comfort by adjusting only the gradient of the friction without changing its magnitude as shown in Fig. 12.

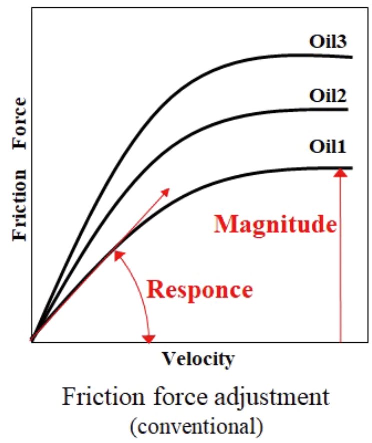

Fig. 11　Technology for changing the magnitude of friction

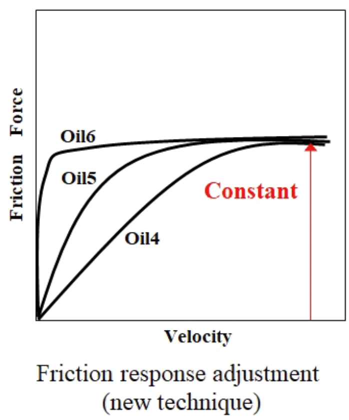

Fig. 12　Technology for adjusting responsiveness

2. 4　Friction influence and related components

In order to evaluate friction characteristics while separating friction response and friction force and develop our own hydraulic fluid technology, we developed our own device as shown in Fig. 13 and use it to examine the evaluation index[5].

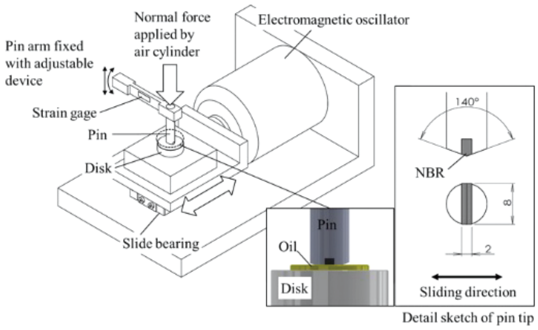

Fig. 13　Schematic of reciprocating force-tester

2. 5　Response index

The Response index (*RI*) was defined as a quantitative index to evaluate the response of friction when the direction of movement was reversed. Fig. 14 shows the range where we extracted the *RI* in the time waveforms of displacement and friction. F_{sa} is the maximum friction in the range from the start of motion up to the phase of $\pi/4$ radians (that is, top and bottom dead centers, $\pi/2$ to $3\pi/4$), and normalizes the difference by the average friction. We divided the difference by the average in order to obtain the acceleration-side *RI* using formula (1).

$$Response\ index\ (RI) = (F_{sa} - F_{ave})/F_{ave},\quad \pi/2 \leqq \theta \leqq 3\pi/4 \qquad (1)$$

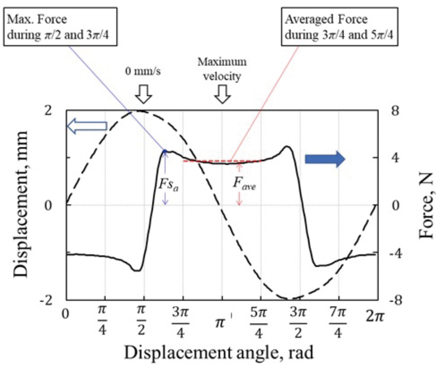

Fig. 14　Calculation concept of the Response index (*RI*)

3　New KYB OIL types and their characteristics

We used our specially made friction test device to develop our own hydraulic fluid technology which can adjust only the response when the direction of motion is reversed without changing the average friction force. Fig. 15 compares the actual characteristics of the oils that we developed with the conventional hydraulic oil characteristics.

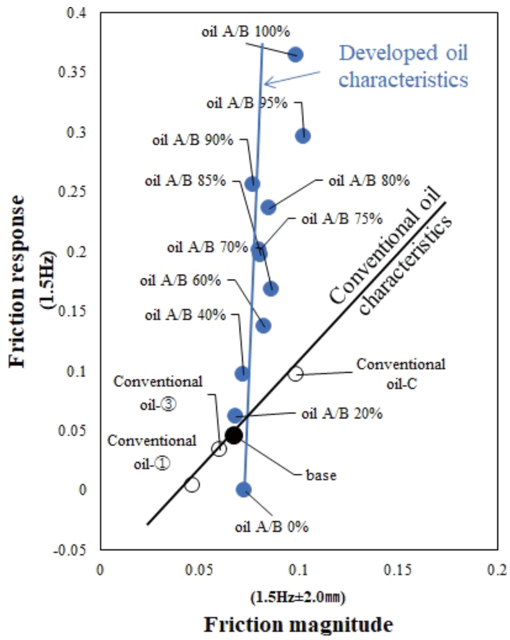

Fig. 15　Characteristics comparison between conventional oils and oils we developed

Hydraulic oil A is a high-response, and the hydraulic oil B is low-response, although the magnitude of friction is almost the same in each case. By changing the blending ratio of these hydraulic oils, it is possible to adjust only the response without changing the magnitude of the frictional force. This technique enables us to investigate the effect of the responsiveness on the basic performance in on-vehicle and bench tests.

4　Oil types Influence on Ride and Handling Performance (Vehicle Assessment Result)

The new KYB oil types and their performance variation on component level were analysed. In order to prove the impact of the oil types on vehicle ride and handling performance, an objective and subjective vehicle assessment is carried out by an engineering service company specialized in vehicle dynamics measurement and assessment.

For this analysis, three sets of SAs with three different oil types, Base (reference, not modified from the original equipment), KYB A/B 100% and KYB A/B 75% are set up. The viscosity of the two KYB oils were adjusted so that it would

Table 1　Oil properties

		Base	A/B75	A/B100
Density (15℃)	g/cm^3	0.83	0.85	0.86
Viscosity index		167	168	152
Kinematic viscosity (40℃)	mm^2/s	11.7	12.9	12.9
Kinematic viscosity (100℃)	mm^2/s	3.3	3.9	3.4

be the same as the Base specification and the influence of kinematic viscosity and the magnitude of friction would not appear [Table 1].

Apart from the oil, the SA hardware and tuning are not changed. It should be mentioned that by not changing the tuning of the SA while changing the oil, the performance might not be optimally balanced at vehicle level, since the tuning is made usually after choosing the oil. However, since the target of this analysis is to isolate the oil impact on vehicle performance, the tuning is not changed. Fig. 16 shows the damping force-velocity characteristics of the three different SA sets. It can be confirmed that there is almost no difference in damping force characteristics, and one would not expect that the vehicle ride and handling performance will be significantly differing.

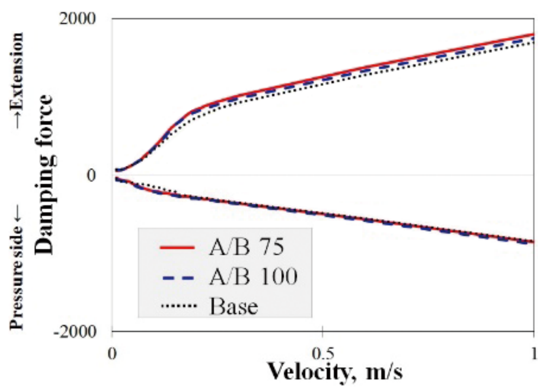

Fig. 16　Damping force-velocity characteristics

4. 1　Objective assessment analysis conditions

The vehicle used for this analysis is a Mercedes-Benz A-Class (W177) which was equipped with various acceleration sensors on knuckle/wheel hubs, top mount at all 4 corners and the seat rail. The full sensor setup is shown in Fig. 17.

The test track on which the measurements have been carried out consist of different road surface types: Nevada (smooth tarmac), South Africa (harsh tarmac) and Country-Road (bad local highway) and a special lane with 30mm steps (3 positive and 3 negative). The vehicle speed was varied between 30-50km/h in steps of 5km/h and from 60-100km/h in steps of 10km/h. Measurements were conducted 3times on every lane and at every speed step, and all of the measurements were averaged for the evaluation. All accelerations, body modes and movements were assessed for each lane, for low, high, and full speed range.

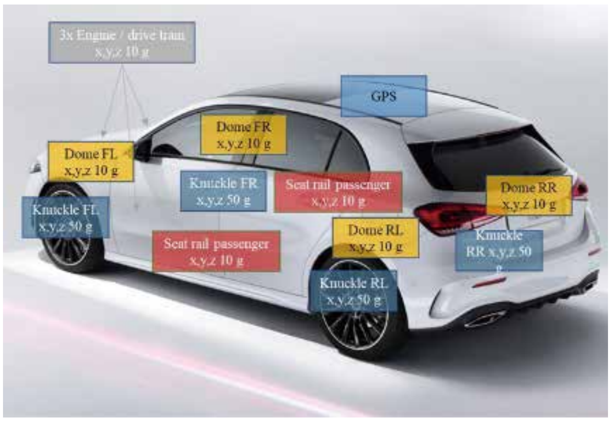

Fig. 17　Vehicle measurement setup

4. 2　Objective assessment results

The results of the analysis are shown in Fig. 18-19. Compared the base configuration shown on the dotted line, the A/B 100% oil shown on the dashed line exhibits a smaller body acceleration in the low-frequency region of 1-2Hz on and larger body acceleration in medium-frequency region of 4-15Hz. The A/B 75% oil shown on the solid line exhibits a smaller body acceleration than the base configuration in both the low- and medium-frequency region.

In general, there is a trade-off to be made when using valves to control the hydraulic force. If the body vibration near sprung mass resonance frequency of 1-2Hz is reduced to emphasize safety, the body vibration of 4-15Hz increases. To emphasize ride comfort, the opposite approach is required[6]. The characteristics are contradictory, making it difficult to achieve both goals. These results show that by simply adjusting the friction responsiveness while keeping the characteristics of the damping force unchanged, it is possible to produce a difference in the vibration levels to achieve both ride comfort and handling. The effect of friction response on the body vibration in the region can be summarized as follows.

Compared to the base configuration, our A/B 100%, which has the highest responsiveness, changes the vibration in a way that emphasizes safety. The A/B 75% oil, which has an intermediate responsiveness between the A/B 100% and the base configuration, does not change the vibration of the 7-15Hz region, and yet decreases vibration in the 1-2Hz region. This oil can be said to improve the stability of the vehicle body without impairing the riding comfort. This improvement, which is generally difficult to achieve with hydraulic valves, appears to be the result of the oil's improved responsiveness, which reduces the acceleration zone in the very low speed range.

We investigated the effect of a SA equipped with this more responsive hydraulic oil on an actual vehicle, and we confirmed that it has a significant impact on handling and ride comfort performance.

Traditionally, when the hydraulic force is adjusted to improve the riding comfort, it is at the expense of safety (manoeuvrability and stability), and vice-versa. We were able to enhance both the riding comfort and safety performance by changing the hydraulic oil to adjust the damping force after the reversal of the direction of motion in a region where it has been difficult to achieve both goals. The results verified that this is an important technique for meeting the requirements for ride comfort and safety depending on the type of vehicle and the customer's preference.

4. 3 Subjective assessment

The subjective evaluation of ride comfort and handling/safety was made on different roads and various conditions such as German motorway (with speed up to 180km/h), well-used roads, potholes, asphalt patches and state roads with conditions between brand new and well-used. Further the assessment was made on the test course containing comfort tracks, simulated state road, single obstacles, handling track, long straight.

As shown in Fig. 20, varying the responsiveness of the oil resulted in significant changes in ride comfort and safety. In addition, we confirmed that it is possible to modify characteristics such as "safety" and "comfort" depending on the purpose and taste of the vehicle.

The subjective assessment of our A/B 100% and

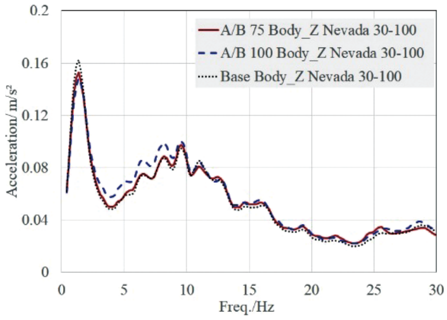

Fig. 18 Vertical Vehicle Body Acceleration for Nevada

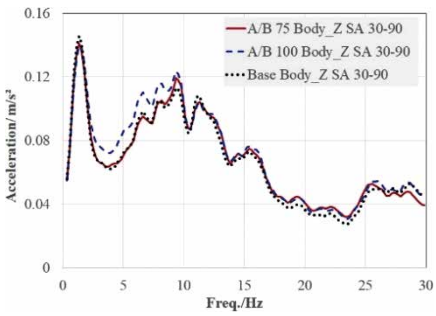

Fig. 19 Vertical Vehicle Body Acceleration for South Africa

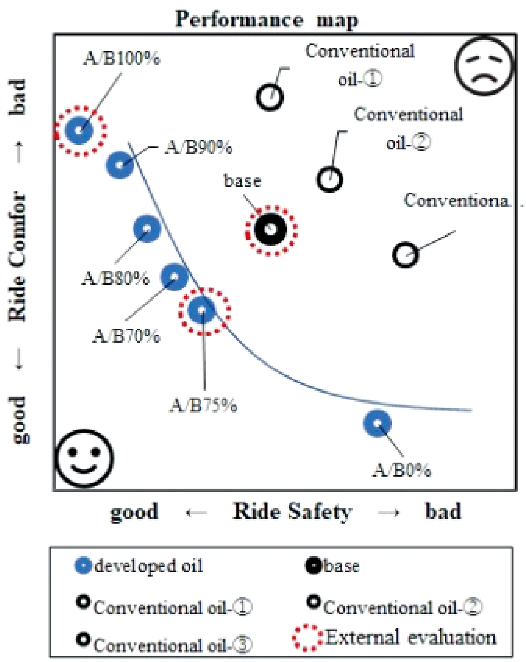

Fig. 20 Response adjustment hydraulic fluid performance

A/B 75% oils compared to the base configuration was also commented by the test driver as if a valve setting such as the bypass or bleed area of the SA were modified. Driving the vehicle with the new oils changes the vehicle dynamics like it has a different positioning e.g. a sport type derivate, or a different manufacturer tuning philosophy.

5 Conclusion

1. When driving on good roads, SAs typically operates in a very-low-speed region between zero (where the direction of motion is reversed) and 30mm/s.
2. On good roads, the very-low-speed region of the SA has a greater effect on the friction force than the hydraulic force, which is very important role of the ride comfort and handling.
3. The conventional friction adjustment technique in a very-low-speed region of the SA, which involves varying the magnitude of friction, has drawback in that it negatively impacts the ride comfort.
4. The friction response was confirmed to be an important factor suitable for safety and ride comfort depending on the type of vehicle and customer preferences.
5. The mechanism of our results is considered from improvement in performance produced by compensating for the damping force that is generated by compressibility of the hydraulic oil in the acceleration zone part of the very-low-speed region in which the direction of motion is reversed.
6. Using the KYB developed oils can open a new dimension of creating variations and optimizing the vehicle drive feel. As the result, we developed a technique that adjusts only the friction response and confirmed that it can improve safety without compromising ride comfort.

6 Outlook

In this paper, we proposed a technique for improving the performance using ordinary conventional SAs, but we anticipate that this technique will improve performance even further if applied to a SA with the latest sated-of-the-art valve structure. In the future, in addition to pursuing the practical application of these results, we plan to further study on the relationship between the friction response and vehicle performance, and will continue to develop the potential of this approach as a new performance enhancement technique.

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