

Development of High-performance PUF and Organoleptic Evaluation of Polyurethane Foam for Car Seat

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ABSTRACT

A polyurethane foam for a vehicle seat cushion was developed in order to improve seat comfort and drivability, as well as to reduce ride vibration and weight. An organoleptic evaluation of seat comfort, which is a static property, was performed by examining hardness, wobbling, bouncing sensations and the bottoming feel, and the correlations between each evaluation marker and the polyurethane foam property values were clarified. For ride comfort, which is a dynamic property, emphasis was placed on the vibrational properties of the human body, and a clear determination was made that adjusting polyurethane properties improves performance. A method for designing the polyurethane foam was established using these results. Using this development method, it was possible to achieve a lightweight seat with superior seat comfort and ride comfort that produced little sensation of vibration or wobbling.

1. Introduction

A desirable vehicle seat cushion is one that gently supports the passenger, is comfortable to sit on, blocks uncomfortable vibrations, and does not wobble when driving. Also, due to the rise in environmental consciousness in recent years, the demand for a lightweight vehicle with improved fuel efficiency has increased greatly.

Polyurethane foam (PUF) is often used these days as the material in vehicle seat cushions. The technology for forming and manufacturing PUF molds was established around 1960, and Honda applied it to the first-generation CIVIC sold in 1974. Presently, cold-cured (HR) PUF has become mainstream, because its high rebound properties allow it to be made thin and it requires little energy to manufacture.

The general method of decreasing the weight of the seat cushion is to decrease the density of PUF. Although PUF is used in the seat cushions of some light vehicles, etc., it has had difficulty providing seat comfort, which is an aspect of static performance. Meanwhile, high-density PUF is being used to improve ride comfort, which is an aspect of dynamic performance. As a result, low-density, high-performance PUF is required.

In order to achieve such a PUF, first the relationship between PUF properties and a human organoleptic

evaluation of static seat comfort was determined, and then a plan for developing the properties to impart to PUF was established, including a control method for dynamic properties. Next, in achieving PUF properties, various PUF property values, such as the polyurethane formulation and F-S properties were revealed, and a development method for controlling properties according to the cell structure of PUF was determined.

Using this development method, it was possible to develop a lightweight, high-performance PUF for a seat cushion.

2. Organoleptic Evaluation of Static Performance

The indicators of seat comfort, an aspect of static performance, were considered to be the feeling of hardness, wobbling sensation, the bottoming feel, and bouncing sensation. In order to determine the relationship between these organoleptic evaluation indicators and PUF properties, various formulations of urethane were used to create test pieces (TPs) with a broad range of property values, and these TPs were used to conduct a static organoleptic evaluation test. The basic concept is shown in Fig. 1.

Here, Indentation Load Deflection (ILD) hardness is the load necessary to push a disk-shaped TP of $\phi 200$ to

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25% and 65% of its thickness, respectively. 25% ILD hardness represents the first touch, and 65% ILD hardness represents hardness when the passenger is stably seated. As Fig. 1 shows, when 25% and 65% ILD hardnesses are both low, the cushion is too soft, and when both parameters are high, the cushion is too hard. In addition, when 25% ILD hardness is low and 65% ILD hardness is high, the first touch is soft, and the cushion tends not to feel wobbly due to the rapid rise in load against stroke. By contrast, when 25% ILD hardness is high and 65% ILD hardness is low, the first touch is hard, but the cushion tends to feel wobbly due to the retardation of the rise of load against stroke.

It was considered that in terms of seat comfort, an ideal balance existed between 25% ILD hardness and 65% ILD hardness, and organoleptic evaluations were carried out on that basis.

2.1. Test Sample

The test samples (TPs) that were used were made by Mitsui Chemical, Inc., and their dimensions were 400 × 400 × 100 mm. Polyurethane foaming with a handmixer was used as the method of producing the TPs, and in order to control the 25% ILD hardness to between 180 N and 300 N using an aluminum polyurethane foam mold, the isocyanate index and density were varied in four types of formulation with the mean molecular weight (Mw) of polypropylene glycol (PPG) in a range of 4,000 to 7,000 (Fig. 2).

2.2. Organoleptic Evaluation Test Method

The panelists were 20 males and females weighing between 45 and 95 kg. The study participants were publicly recruited and participated according to their own free will. After these participants were provided with a sufficient written explanation of the study, organoleptic evaluations were performed according to the study method shown in Fig. 3 and Table 1. Also, this test was

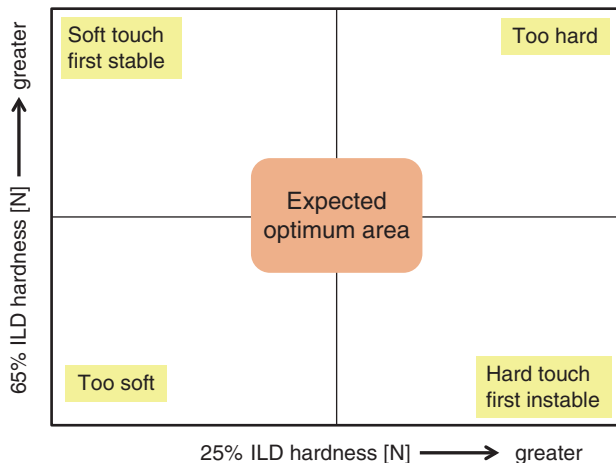


Fig. 1 Material characteristics of polyurethane

Table 1 Procedures of organoleptic evaluation method

Feeling	Test method
Feeling of hardness	Sit still on a seat and make a sensory evaluation on a 6-point scale.*1
Wobbling sensation	Based on urethane test piece equivalent to the reference one, swing upper body back and forth and around to make a sensory evaluation on a 6-point scale.
Bottoming feel	Stand up from urethane test piece and sit down to make a sensory evaluation on a 5-point scale.*1
Bouncing sensation	

*1 (To correct feeling change with the passage of time, compare seating comfort with reference samples and other test piece.)

performed after obtaining the approval of the Honda Bioethics Committee.

2.3. Results of Organoleptic Evaluation Study

2.3.1. Feeling of hardness and ILD hardness

Generally, 25% ILD hardness is used as the indicator for PUF hardness in seat cushion pads for vehicles. In this instance, organoleptic evaluations of PUF were performed by varying PUF properties in various PUF formulations, and a correlation was found between ILD hardness and the feeling of hardness. As Fig. 4 shows, the coefficient of correlation was higher for 65% ILD hardness.

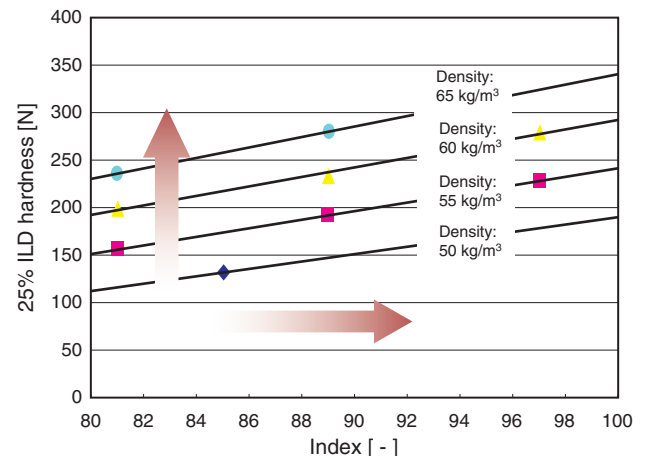


Fig. 2 Hardness controlled under different density and indexes

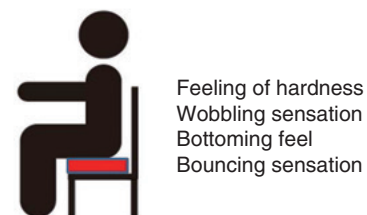


Fig. 3 Organoleptic evaluation method

2.3.2. Sensation of wobbling and sag factor

Figure 5 shows the results of using the TPs to test the correlation of the sag factor, which is the ratio of 25% ILD hardness and 65% ILD hardness. An extremely high correlation was found between the sensation of wobbling and the sag factor. These results show a higher correlation than in Fig. 6, which shows the 25% ILD hardness, 65% ILD hardness, and the sensation of wobbling.

2.3.3. Bottoming feel and sag factor

The correlation between the bottoming feel and the sag

factor is shown in Fig. 7. It was found that when the sag factor is in a range from 2.6 to 3.0, bottoming is difficult to feel. When the sag factor is in excess of 3.0, the load rise in the sag process is felt as the bottom of the seat. When the sag factor is at or below 2.6, the load with respect to sagging does not rise, so the stroke weight with respect to the load increases, and finally the load suddenly rises, causing the bottoming feel.

2.3.4. Bouncing sensation and hysteresis loss rate

A correlation was observed between bouncing sensation

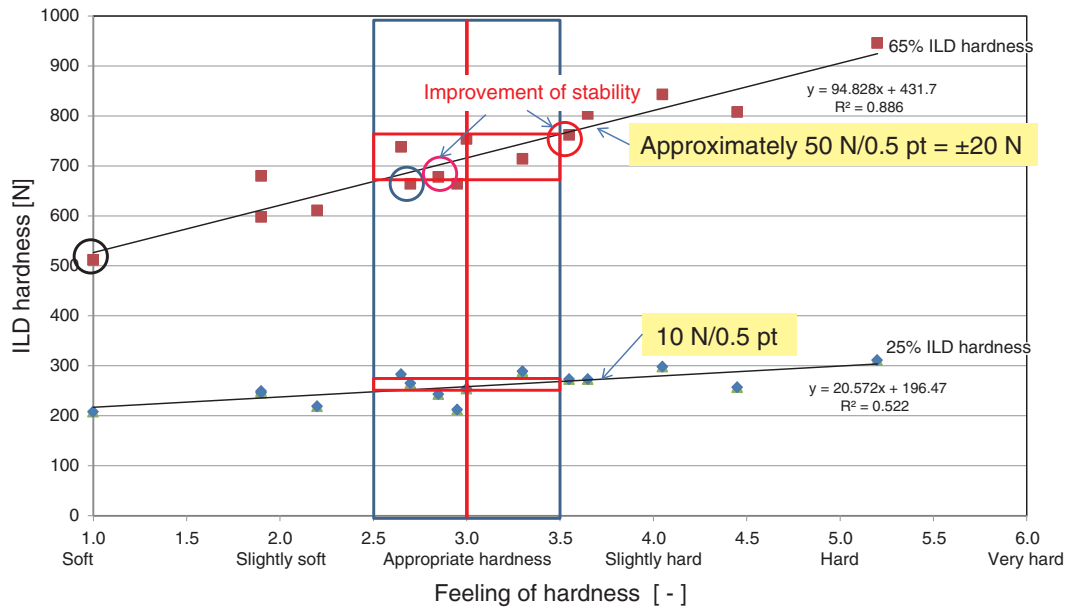


Fig. 4 Feeling of hardness and ILD hardness

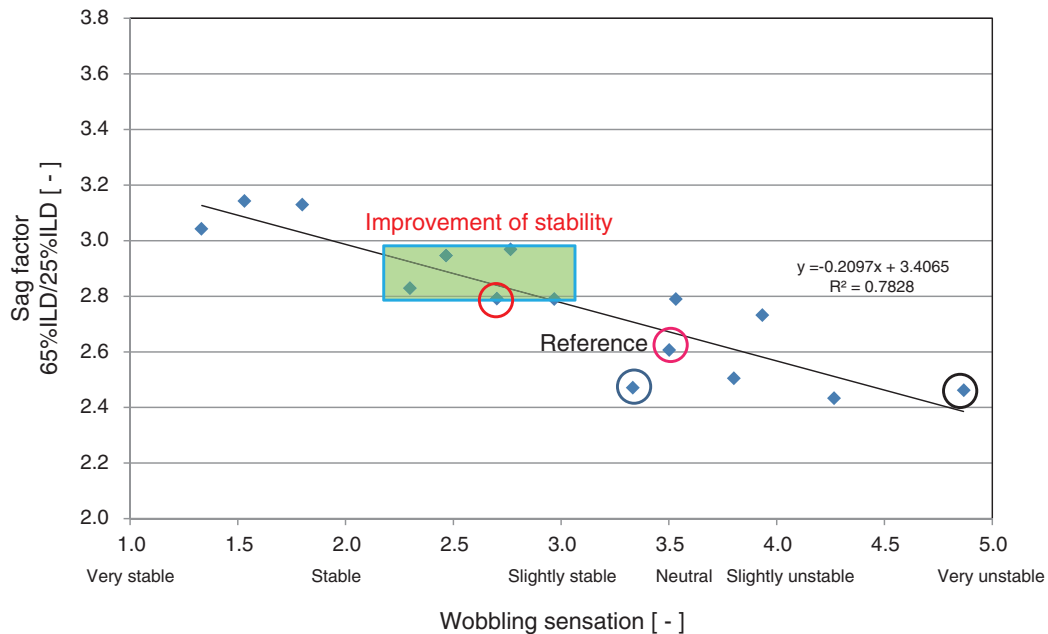


Fig. 5 Relationship between wobbling sensation and sag factor

and the hysteresis loss rate (Fig. 8). The red surface area represents the hysteresis loss when unloading from the compression of F-S properties. It was observed that as the hysteresis loss rate dropped, bouncing was felt more intensely. As for vibration absorption that affects the bouncing sensation, it is known that the heat energy conversion is caused by hysteresis loss of resin as well as the airflow resistance of the PUF cell. With TPs that are produced under the same conditions, when the conditions

for crushing those TPs immediately after foam formation are varied and the TPs are strongly crushed, airflow improves and bouncing sensation heightens.

2.3.5. Comfortable hardness range obtained from hardness feel and wobbling sensation

Comfort level during static sitting at 25% ILD hardness, 65% ILD hardness and static sitting was used as the main indicator for the organoleptic evaluation. As a result of

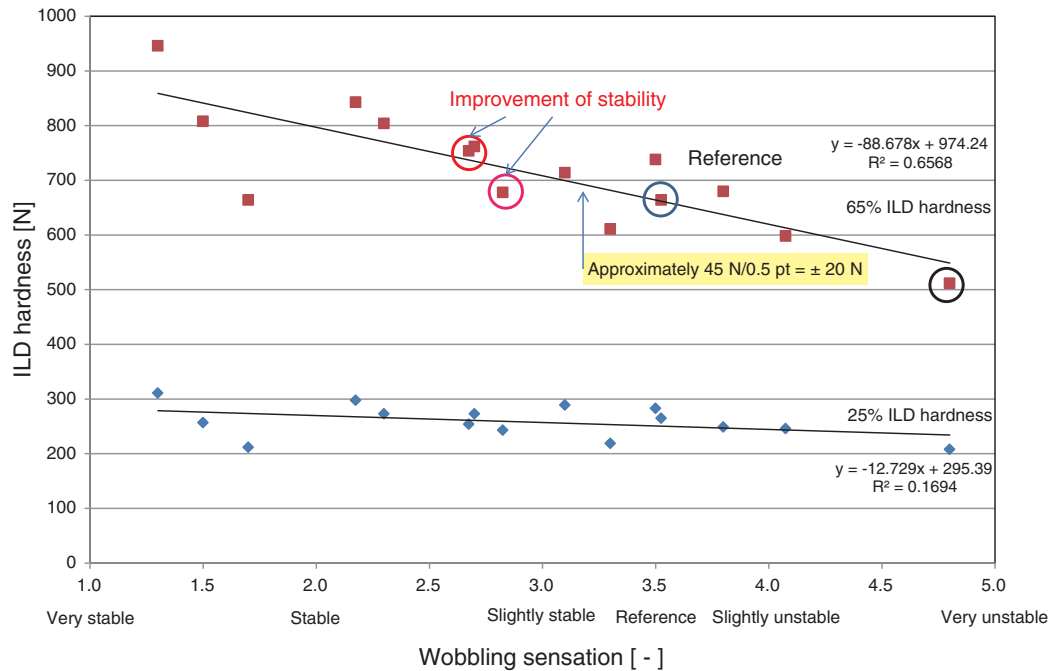


Fig. 6 Wobbling sensation and ILD hardness

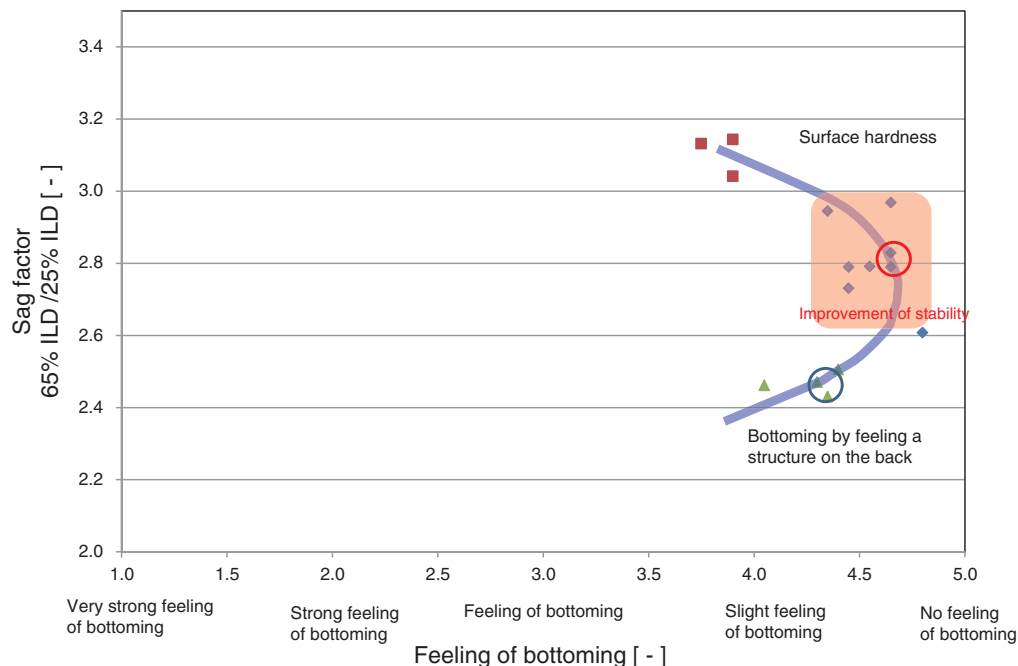


Fig. 7 Relationship between bottoming feel and sag factor

Table 2 Feelings and urethane foam characteristics

	Urethane compression Physical property					Ventilation volume
	25% ILD hardness	65% ILD hardness	Sag factor	Hysteresis loss rate	Impact resilience rate BR%	Ventilation volume
	25% compression Reaction force	65% compression Reaction force	Value obtained by dividing 65% ILD hardness by 25% ILD hardness	Rate of mechanical energy loss during 1 cycle of compression deformation and recovery	Height of an iron ball bouncing back when it is dropped	<Vibration absorption> Approximate energy loss due to ventilation resistance of urethane cell
Feeling of hardness	○	◎				
Wobbling sensation		◎	◎			
Bottoming feel	(○)	(○)	◎			
Bouncing sensation				◎	◎	◎
Comfort level	○	◎	◎			

○ : Good

◎ : So good

interviewing the panelists, it was found that the judgment for comfort level is made based upon the feelings of hardness and wobbling. As shown in Fig. 9, even from the viewpoint of hardness feel and wobbling sensation, perceptions of somewhat comfortable and somewhat uncomfortable often occurred together at the same level of hardness at 25% ILD hardness. However, at 65% ILD hardness, comfort level and hardness could be easily differentiated. For this and other reasons, it was determined that 65% ILD was an effective hardness indicator, in addition to the conventional hardness indicator of 25% ILD.

2.4. Summary of Static Performance and PUF Properties

The correlation between static seat comfort and PUF properties is summarized in Table 2. It is necessary

to increase the efficiency of seat development and the stability of mass-production quality by clearly showing the properties required for improving reproducibility and the optimal ranges within which to control those properties.

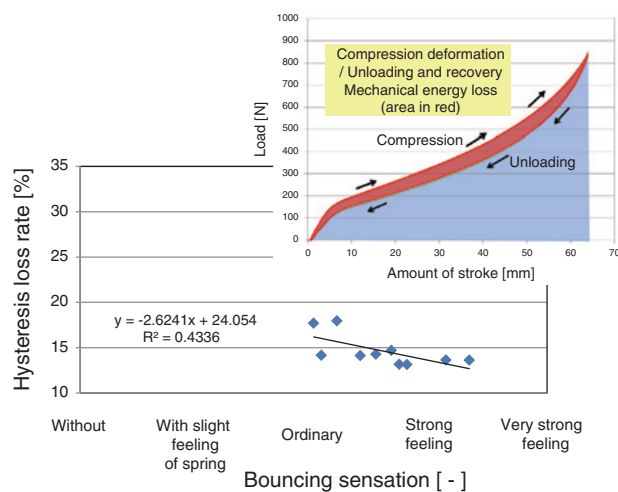
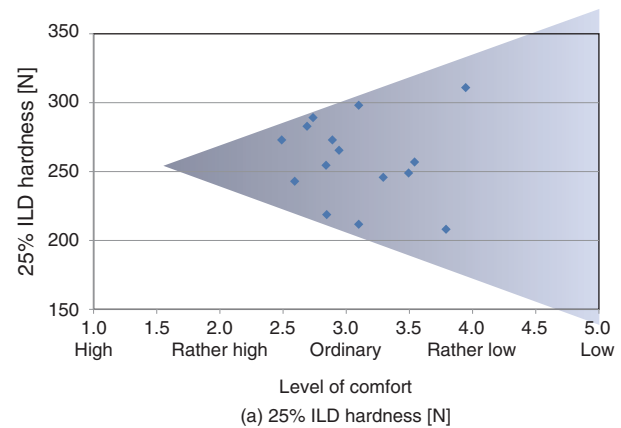
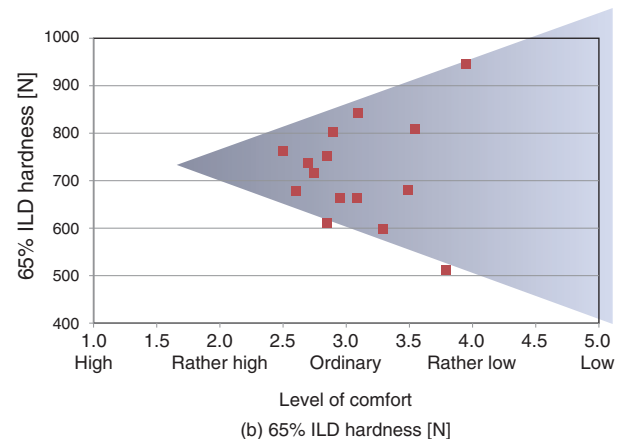


Fig. 8 Relationship between bouncing sensation and hysteresis loss rate



(a) 25% ILD hardness [N]



(b) 65% ILD hardness [N]

Fig. 9 Hardness of polyurethane test piece and level of comfort

3. Dynamic Performance Evaluation

3.1. Dynamic Performance and Resonance Frequency of Human Body

The measurement results of the input acceleration from the vehicle body during actual vehicle traveling are shown in Fig. 10. Peaks exist from 1 Hz to 2 Hz, 4 Hz to 8 Hz, and 10 Hz to 20 Hz. Vibrations from the vehicle body are transmitted from the seat frame through the urethane pad to each part of the human body. These vibrations are transmitted to the human body as the following sensations: bobbing up and down at 2 to 4 Hz; pressure on the abdomen at 4 to 8 Hz; and roughness, trembling, and vibrating sensations to the thighs at 8 Hz and above.

In addition to blocking vibrations from the vehicle body and reducing uncomfortable vibrations at or above 4 Hz, which are easily perceived by the human body, it is also important to reduce resonance in order to minimize car sickness and fatigue.

3.2. Dynamic Performance and PUF Properties

Vibrational input from the vehicle body being received by a human sitting on a urethane pad is shown in a simple model (Fig. 11). The resonance frequency f_0 Hz changes

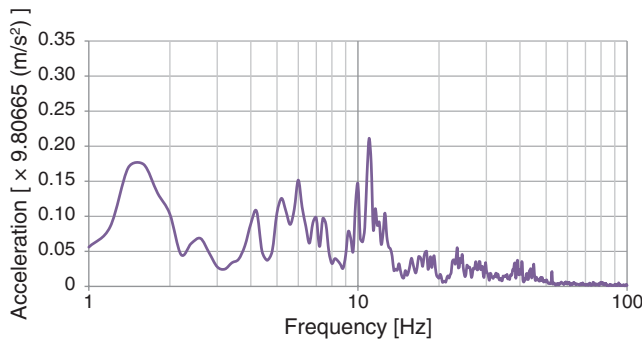


Fig. 10 Input acceleration from body (Attachment point of front seat)

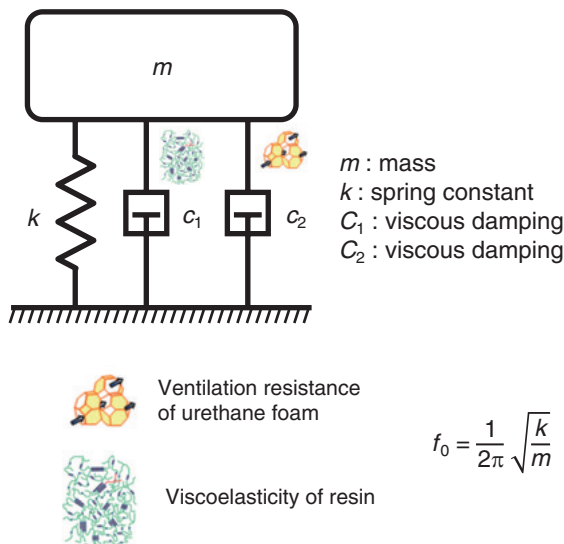


Fig. 11 Viscosity mass damper with spring model of PUF

according to the spring constant, and decreasing the spring constant when a person is sitting in the seat lowers the resonance frequency, as shown in Fig. 12.

From the perspective of ride comfort, which is an aspect of dynamic performance, it is preferable to lower the PUF resonance frequency, shifting to the low-frequency range, and decrease the vibrations transmissibility in all ranges by decreasing the resonance magnification.

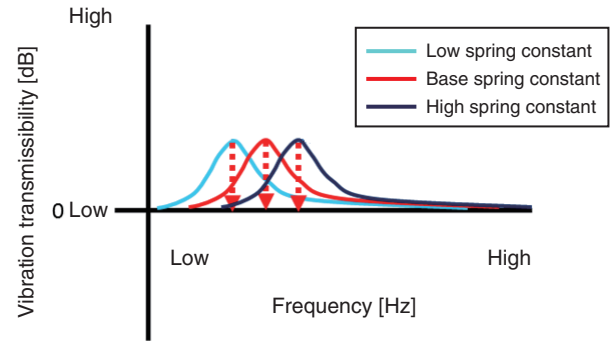


Fig. 12 Movement by spring rate of resonance frequency

4. Design Method

The correlation between the urethane resin design and the PUF cell structure plays an important role in the vehicle seat. This correlation is summarized with respect to the sag factor and vibration blocking, which affects wobbling sensation, which greatly affects body stability.

4.1. ILD Control

ILD is highly correlated with the feeling of hardness. Generally, ILD is adjusted to 25% by adjusting the isocyanate index and density. However, it is difficult to use this method to control the desired values of both 25% ILD and 65% ILD. The PPG molecular weight and polymer polyol (POP) quantity are important in designing hardness in the optimal property region shown in Fig. 1.

4.2. Sag Factor and PPG Molecular Weight

As Fig. 13 shows, the molecular weight of polyols has a significant effect on the sag factor, which in turn significantly affects the wobbling sensation. Figure 14 shows a schematic diagram of polyurethane resin. Phase separation between PPG and amino bases tends to occur more in polyurethane resin that uses high-molecular-weight PPG as opposed to low-molecular-weight PPG. When phase separation occurs, the hard segment formed by isocyanate and a chain-extending agent increase, causing initial elasticity to be higher. Also, the soft segment comprising mainly PPG has a high-molecular-weight chain that easily extends. Viewed from the standpoint of PUF properties, these are F-S properties in which it is difficult for a load to stand even at a high stroke.

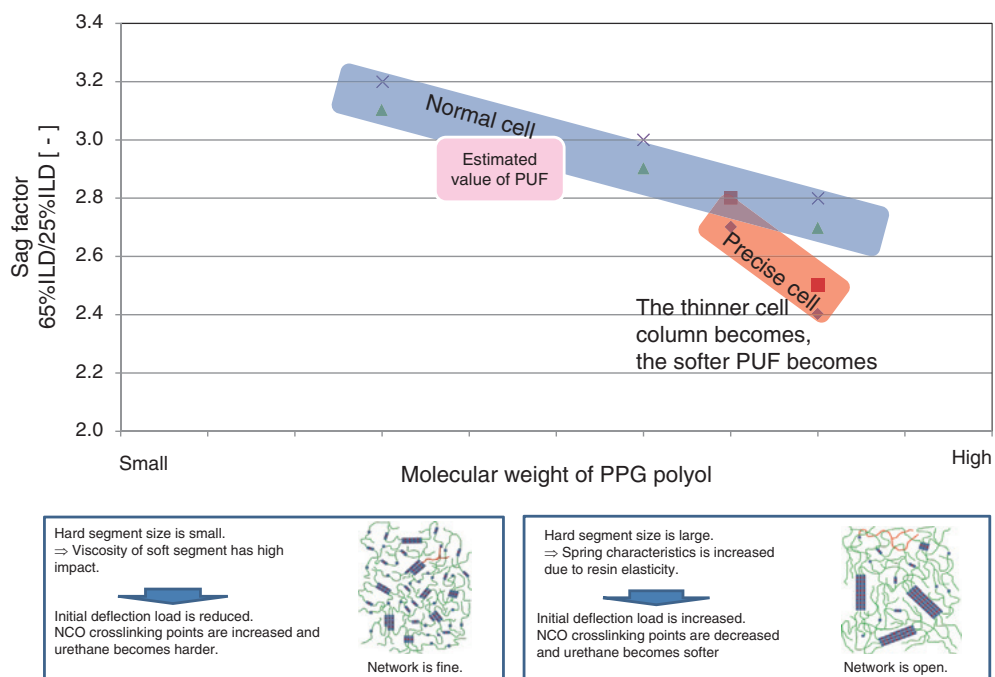


Fig. 13 Sag factor and molecular structure

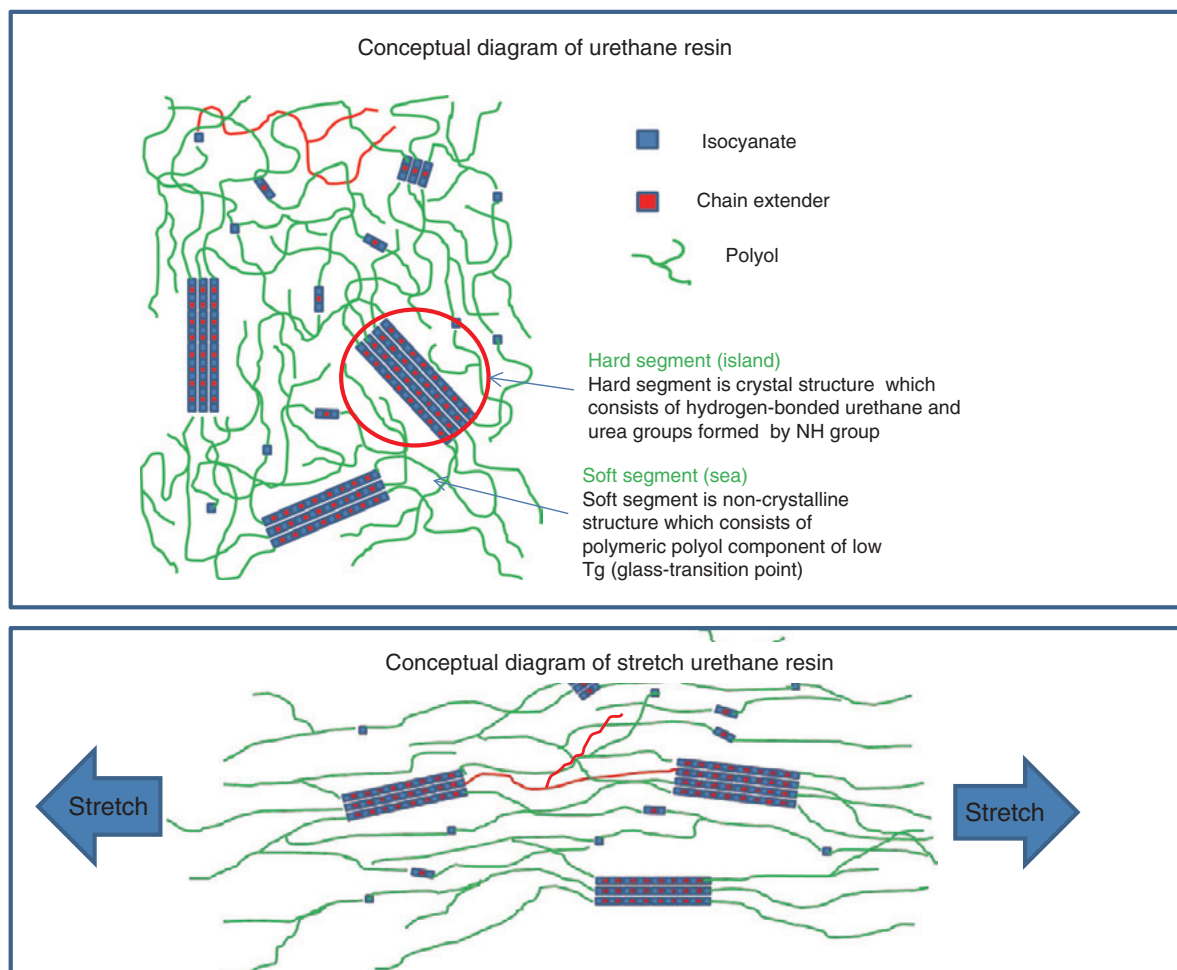


Fig. 14 Schematic diagrams of polyurethane

4.3. Combination of Dynamic Performance and Wobbling Sensation

As shown in Fig. 13, when viewed from the perspective of urethane resin design, there is a large effect caused by the molecular weight of PPG, which is a component of polyol, and it was found to be possible to lower the resonance frequency by using high-molecular-weight PPG. However, if the value of the spring constant k is decreased by simply using high-molecular-weight PPG, the resonance frequency will decrease but the resonance magnification will increase, as shown in Fig. 15. As Fig. 13 shows, high-molecular-weight PPG decreases the sag factor, and when the sag factor decreases, it becomes easy to sense wobbling. Therefore, it is important to find a balance between the sag factor and the sensation of wobbling. When simply changing the PPG to a high-molecular-weight PPG, airflow increases as a result of changing to open cell, and resonance magnification increases. By optimizing the type and weight of the silicon-based foam stabilizer, the airflow

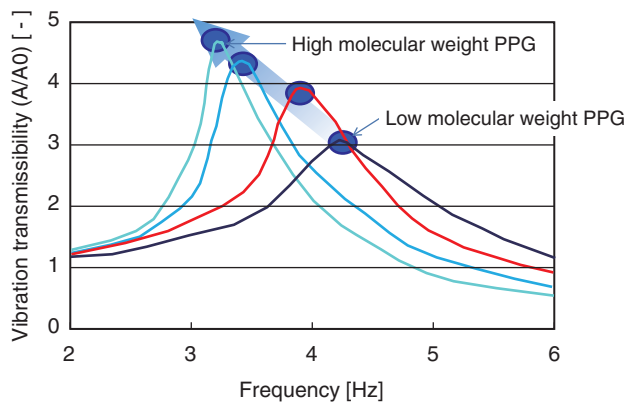


Fig. 15 Molecular weight and vibration transfer characteristics of PPG

resistance is increased in a compact cell structure and the resonance magnification is decreased. Airflow rate and resonance magnification are related as shown in Fig. 16. It was discovered that by setting the cell size and crushing conditions to yield the optimum airflow rate, the resonance magnification is reduced, making it possible to achieve a balance with resonance frequency. The same change in resonance frequency and change in sag factor were observed even when the PPG and POP formulation ratio was changed.

4.4. Summary of PUF Design Method

In terms of static performance, this analysis showed a correlation between the sag factor, which greatly impacts wobbling sensation, and the molecular weight of PPG (Fig. 13) and a correlation between the hysteresis loss rate and the molecular weight of PPG (Fig. 17). In addition to the conventional 25% ILD hardness management based on the density and isocyanate index, it was discovered that it was important to specify a hysteresis loss rate for which it is possible to specify the molecular weight of PPG, which

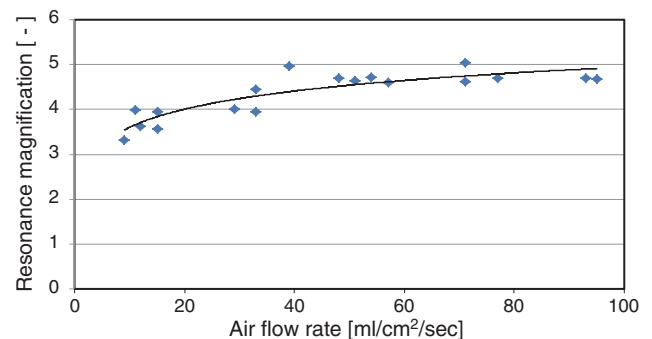


Fig. 16 Air flow rate and resonance magnification

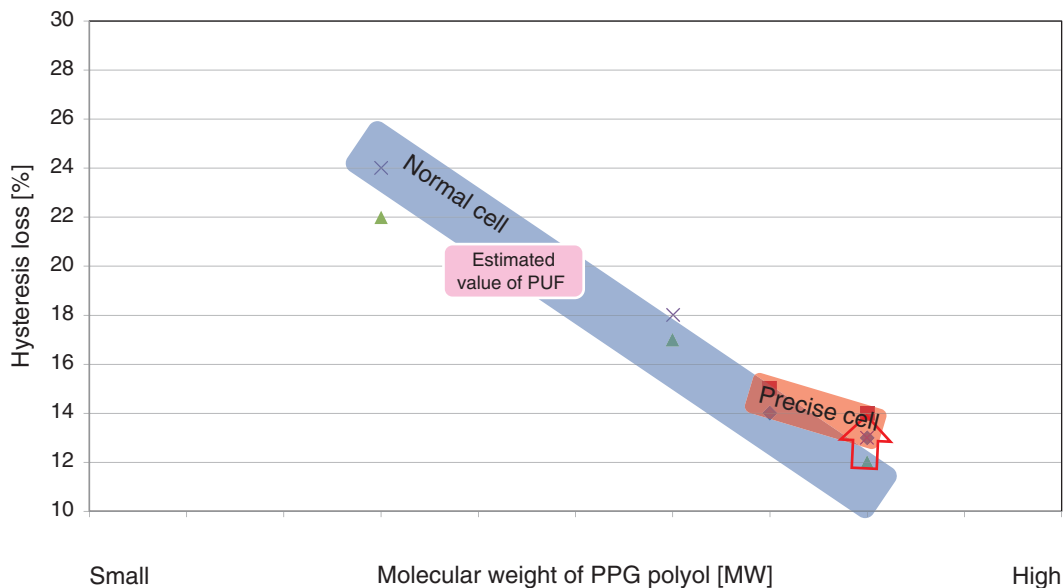


Fig. 17 Hysteresis loss rate and molecular structure of PPG

Table 3 Specifications of flexible PUF (400×400×100 mm)

		Unit	Development	Reference existing mass-produced low repulsion urethane	Reference high density product urethane
Density	Dcore	kg/m ³	63	63	83
Hardness	25%ILD	N	250	245	250
	65%ILD	N	730	700	675
Hysteresis loss rate		%	<15	19	14
Repulsive elastic core		%	>65	65	68
Resonance frequency		Hz	3.3	3.6	3.3
Resonance magnification (A/A0)		-	2.6	2.6	2.8
6 Hz transmissibility (A/A0)		-	0.6	0.8	0.65
10 Hz transmissibility (A/A0)		-	0.2	0.3	0.28

greatly affects the sag factor of the 65% ILD hardness and wobbling sensation indicator that is the comfortable hardness indicator.

Also, in terms of dynamic performance, a high correlation was observed between the resonance frequency and hysteresis loss rate (Fig. 18) and between the hysteresis loss rate and the molecular weight of PPG (Fig. 17). Also, it was discovered that the molecular weight specification of PPG required for obtaining the desired resonance frequency could be substituted with the hysteresis loss rate. This indicated that it would be possible to regulate the limit for the molecular weight of PPG, the main component of polyols, and major aspects of performance such as the resonance frequency of the urethane vibration characteristic by specifying the hysteresis loss rate. Also, the resonance magnification could be estimated by specifying the airflow rate.

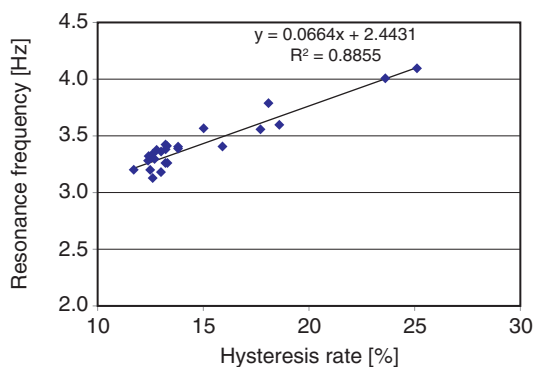


Fig. 18 Hysteresis loss rate and resonance frequency

5. High-performance Seat Development

5.1. Goals

In developing PUF material for vehicle seats, we developed a PUF (“developed PUF”) with new properties

having the following four main goals:

- (1) An appropriate hardness feel
- (2) A superior vibration-damping property
- (3) A wobbling sensation equivalent to that of the conventional PUF
- (4) Reduced weight

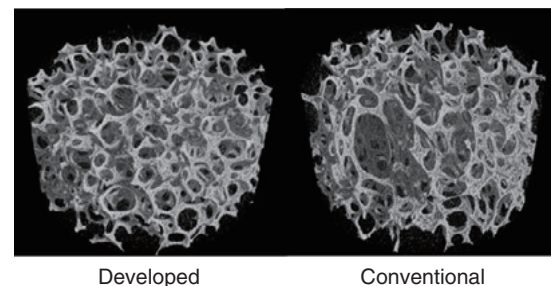
5.2. Developed PUF Characteristics

The main specifications of the developed PUF are shown in Table 3. The developed PUF is soft with a core density of 63 kg/m³, which is the same as mass-produced, low-density urethane. The developed PUF has a low resonance frequency and reduced vibration transmissibility at all frequencies. Also, it has a seat comfort at the same level of the 80 kg/m³ high-density PUF, a low wobbling sensation, an appropriate bouncing sensation, and superior vibration-damping property.

Fig. 19 shows an X-ray microtomography image of the developed urethane and the current mass-produced, low-density urethane. The developed urethane has finer and more uniform cells compared to the mass-produced, low-density urethane, and it has a structure with greater airflow resistance between cells.

5.3. Concept of the Developed PUF Design

The urethane resin of the developed PUF uses high-

Fig. 19 X-ray Microtomography $\phi 3$ mm 3D View

molecular-weight PPG of a low monool and has a low hysteresis loss rate. It achieves a balance between the wobbling sensation and vibration properties. Specifically, the resonance frequency is reduced by using a high-molecular-weight PPG to decrease the bouncing sensation. Also, the type and weight of the silicon-based foam stabilizer are optimized, resulting in a compact urethane cell structure and optimized crushing quantity. This improves the vibrational absorption performance of the air damper, minimizing resonance magnification and improving the 6-Hz and 10-Hz vibration-damping property.

Figure 20 shows the F-S properties of typical urethane. The developed urethane has vehicle cushioning urethane that is neither too soft nor too hard and causes little wobbling sensation. Also, the developed urethane was similar to the MDI urethane used in Europe, and the 65% ILD hardness value was found to be almost the same.

When urethane resin is designed using low-molecular-weight PPG at the identical 25% ILD hardness, the slope of the F-S properties increases and the PUF becomes hard, causing the bottoming feel. This is illustrated by the red-purple line in the diagram. Meanwhile, when high-molecular-weight PPG is used, the F-S properties slope flattens out, as illustrated by the blue line in the diagram. The PUF is soft and tends to allow a wobbling sensation. Although this PUF has extremely excellent vibration-damping property, the wobbling sensation is too great in the actual seat. Therefore, countermeasures are required.

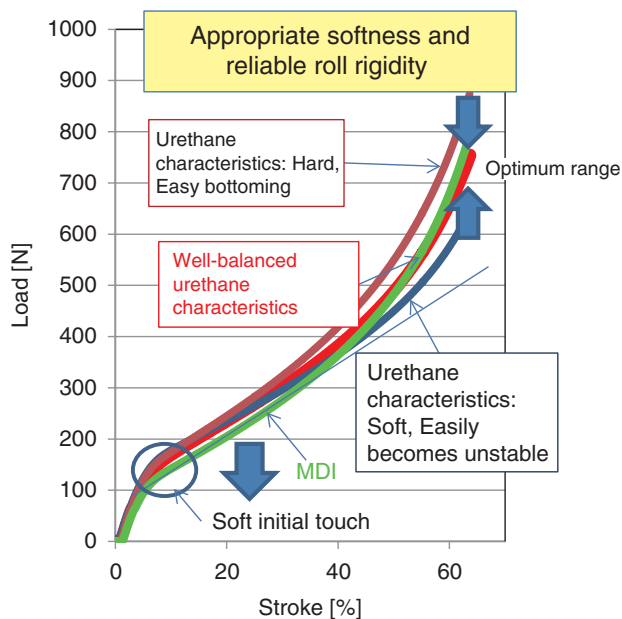


Fig. 20 Compression load characteristics of flexible PUF 400×400×100 mm

Table 4 Specifications of trial seat

Cushion frame	Pan frame
Cushion pad thickness (HP)	105 mm
PUF density (core)	63 kg/m ³
Hardness 25%ILD (Pad)	245 N
Hardness 65%ILD (Pad)	790 N

Figure 21 shows the vibration properties when 100-mm-thick PUF is used. The red line in the diagram represents the developed product. Compared to the mass-produced vibration absorption urethane shown in the black line in the diagram, the developed product exhibits a lower resonance frequency and a lower resonance magnification. Also, the developed product has lower vibration transmissibility in the range of 4 to 8 Hz, which is the range that is easily perceived by the human body. The blue line represents the PUF property before countermeasures were taken for wobbling sensation. Although the vibration-damping property is extremely high, countermeasures were required due to high wobbling sensation in the actual seat.

5.4. Organoleptic Evaluation of Developed PUF Seat

Experts conducted an organoleptic evaluation of the developed PUF in a test course drive by installing a test seat having the specifications shown in Table 4 in a vehicle. The results obtained from that evaluation are shown in Table 5. A well-balanced seat was achieved by improving of softness, vibration attenuation, and rolling stiffness (wobbling sensation). These aspects were improved by changing the molecular weight of the PPG in the PUF in order to increase the bouncing rate and thus decrease the load during low stroke.

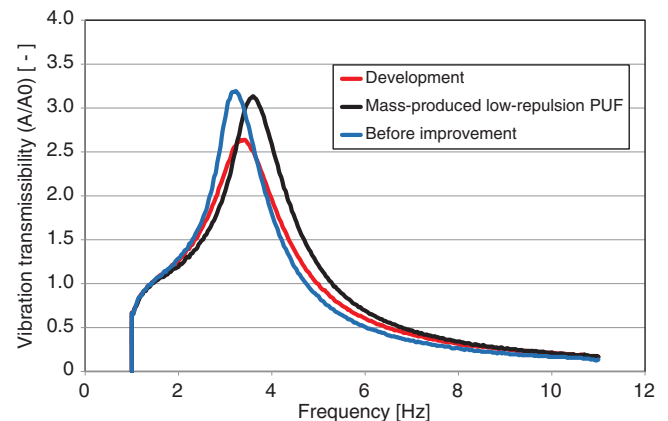


Fig. 21 Vibration transmissibility of PUF 400×400×100 mm

Table 5 Organoleptic evaluation of test track driving

	Structure with spring				Full pan structure			
	Mass-production foam		Foam with formulation to reduce wobbling sensation	High resilience and high-vibration absorption foam after reducing wobbling sensation		High resilience and high-vibration absorption foam after reducing wobbling sensation	High resilience and high-vibration absorption foam before reducing wobbling sensation - baseline	
Soft-touch feeling	- Felt	-0.5 x	- Slight permanent set - Felt	-1 x	- Felt	+1 ○	- Felt	+1 ○
Damping feeling	- Choppy road (US) 80 - 100km/h large vertical motion - Vibration not absorbed when suspension fully stroked.	± 0	- Choppy road less vertical motion - Vibration absorbed when suspension fully stroked - Unsteadiness of spring hardly felt	+1 ○	- Choppy road less vertical motion - Vibration absorbed when suspension fully stroked - Slight stroke observed and sufficient thickness of foam felt	+1 ○	- Choppy road less vertical motion - Vibration absorbed when suspension fully stroked - Slight stroke observed and sufficient thickness of foam felt	+1 ○
Rolling stiffness feeling	- Rolling observed when turning corner	± 0	- Movement of spring felt but rolling stiffness sufficient	+1 ○	- Good firmness	+1.5 ◎	- Good firmness	+1.5 ◎
Shaky feeling	- Hardly felt	± 0	- Not felt other than at belly	-0.5 x	- No	± 0	- No	± 0
Fluffy feeling	- Felt	-0.5 x	- No	± 0	- No	± 0	- No	± 0
Rebound feeling	- Slightly felt	-0.5 x	- No - Felt thinner than actual	-1 x	- Firmness, felt thicker than actual	+0.5 ○	- Firmness, felt thicker than actual	+0.5 ○
Bottoming feeling	- No	+1 ○	- No - Slight vertical acceleration felt at suspension bottoming	+0.5 ○	- No - Right amount of stroke, a sense of fullness	+1.5 ◎	- No - Right amount of stroke, a sense of fullness	+1.5 ◎

◎ : So good ○ : Good x : Poor

6. Summary

A PUF with excellent properties for a vehicle seat cushion was developed. A soft PUF that wobbled little and maintained posture well was achieved by determining the optimal region for the molecular weight of the high-molecular-weight PPG and the POP formulation ratio. Optimizing the type and weight of the high-molecular-weight PPG and silicon-based foam stabilizer and optimizing the crushing conditions allowed vibrations that are uncomfortable to the human body to be blocked.

This developed PUF provides superior seat and ride comfort not only when using a pan-frame seat, but also when using a bouncing-frame seat.

The following findings were simultaneously made during this research:

- (1) The important PUF properties to control that reproduce the organoleptic evaluation indicators are density, 25% ILD hardness, 65% ILD hardness, hysteresis loss rate, rebound elasticity rate, and airflow.
- (2) The molecular weight of PPG and the POP formulation ratio greatly affect PUF properties, and the effect is particularly large on the sag factor, which represents load sagging, and on the hysteresis loss.
- (3) In vibration blocking, the resonance frequency is reduced by switching to a high-molecular-weight PPG. The resonance magnification is lowered by optimizing the silicon-based foam stabilizer type and quantity as well as the crushing conditions. There are also conditions that minimize the transmission rate of vibrations that are uncomfortable to the human body.
- (4) The properties required for a urethane resin design that greatly affect seat and ride comfort were clarified, and PUF reproducibility was improved.

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