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DESIGN GUIDELINE FOR THE IMPROVEMENT OF DYNAMIC COMFORT OF A VEHICLE SEAT AND ITS APPLICATION

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ABSTRACT−This study proposes an innovative design guideline to assist the evaluation and improvement of the dynamic comfort of vehicle seating. The existing evaluation method for the comfort of vehicle seating was investigated to broach problems in evaluation. It was found that the currently existing evaluation method employs the resonance frequency of the vibration system composed of the seat and the human body and the maximum vibration transmissibility. This study proposes a design guideline aimed at the enhancement of vibration transmission characteristics above the resonance range, particularly within the range of 10−18 Hz. In order to meet this guideline, a seat was constructed out of foam having a low damping coefficient. It was then installed in a vehicle for a driving test. The driving test confirmed the improvement of the dynamic comfort of the seat. The result of evaluation of the improved seat using the SEAT index, an industry standard widely used to evaluate the dynamic comfort of a seat considering the perceptivity characteristics of the human body, showed that the perceptive vibration transmission had reduced by more than 11%. The effect of the modification of seat foam was also verified through a subjective assessment of dynamic comfort of the seats.

KEY WORDS : Dynamic comfort, Vibration transmissibility, Low damping foam, SEAT index, Perceptive vibration

1. INTRODUCTION

The function of vehicle seating is to provide a driver with safety, practicality and comfort. While a basic seating design scheme to secure both practicality and safety has already been secured, seating design considering comfort is comparatively less systemized because 'performance' and 'safety' have been the concerns of highest priority throughout the history of vehicle development. Since 'performance' and 'safety' have been stabilized through continuous technological development, vehicle comfort has recently become an important theme having great potential to enhance the competitiveness of a vehicle. Among the components of which a vehicle is comprised, the seat is the primary medium through which a driver contacts with the vehicle. Therefore, it has a large impact on the overall comfort level (Brunning and Day, 1997). The comfort of a seat can be further divided into static comfort and dynamic comfort. In particular, after the 1990's, the majority of studies for the improvement of seating comfort have been concentrated on dynamic comfort. However, no specific design guideline for dynamic comfort has been yet established.

This study presents an innovative design guideline for the improvement of the dynamic comfort of vehicle seating and its evaluation method which is believed to have a strong point in the practical viewpoint. Applicability of the design and the method has been verified by applying them to the improvement of the actual vehicle seat. The present study discussed and raised, the problem with the currently used evaluation method of the dynamic comfort using resonance frequency and maximum vibration transmissibility of the 'seat-human body' system. A solution to this problem was proposed with the seat dynamic characteristics determination method to improve the dynamic comfort of a seat in a vehicle environment. The superior seat as proposed by this study was constructed and the effect of the improvement was examined through the results of a driving test.

2. PREVIOUS WORKS ON THE EVALUATION OF DYNAMIC COMFORT OF A SEAT

2.1. Development of Objective Measure of Sitting Comfort

Vehicle vibration accelerates the fatigue of the driver/passenger while driving for an extended period of time. Studies on the influence of the drive by a vibrating vehicle began in the latter half of the 60's. In 1968, Van Deussen analyzed the range of vibration magnitude by

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frequency, examined how this influenced the human body, and presented the range of vibration magnitude by frequency where comfort is secured. Stikeleather (1972), who extended Van Deussen's above study, emphasized the role of the seat in isolating the vibration transmitted to the driver/passenger. It can be said that this study was the first study to introduce the concept of dynamic comfort as a requirement for the seat.

In the meantime, those who were involved in the research and development of vehicles attempted to evaluate the comfort that was determined by the driver's subjective perception using quantitative value. Through a series of studies, Vartersian (1977, 1982) proposed the following equation for the evaluation of dynamic comfort that was different from all other previous ones.

$$R = \frac{K}{f_n \cdot A \cdot B} \tag{1}$$

Where,
K : Constant according to the type of seat
f_n, A : Resonance frequency and maximum vibration transmissibility
B : Vibration transmissibility at 10 Hz.

With the above equation, Vartersian asserted that the comfort increased as the resonance frequency became lower, that is, as the seat rigidity decreased. His theory is rather unrealistic in that his equation does not consider the driver's workability in the seat. Nevertheless, the equation is meaningful in that it represents the dynamic comfort of a seat in quantitative value. In particular, it can be said that he made a realistic attempt by treating the transmissibility of vibration having a frequency of 10Hz, where the secondary resonance of the vehicle suspension system and engine mounting frequency are close.

Griffin (1990) proposed the SEAT (Seat Effective Amplitude Transmissibility) that was able to represent the vibration isolation characteristics of a seat quantitatively as follows:

$$SEAT(\%) = \left[\frac{\int G_{ss}(f) \cdot W^2(f)df}{\int G_{ff}(f) \cdot W^2(f)df}\right]^{1/2} \times 100 \tag{2}$$

Where,
$G_{ss}(f)$, $G_{ff}(f)$: Acceleration power spectrum at seat cushion and floor, respectively
$W(f)$: Function of frequency weight factor due to vibration of the human body, which is provided from ISO 2631-1(1997).

He evaluated the dynamic comfort of a seat by quantifying the vibration perceived by the human body (driver) using the frequency-weighting factor. This factor has been widely utilized to evaluate human response to vibration of a seated person. As the studies for the evaluation and improvement of the dynamic comfort of vehicle seating were more actively performed, the application of the SEAT value was further generalized by Goldsheyde and Willems (1996), Kinkelaar, Neal and Crocco (1998), and Cho, Park and Yoon (2000). This value is also widely used to evaluate not only the dynamic comfort of the seat but also the characteristics of foam, which is the raw material comprising the seat.

2.2. Design Criteria for Securing Dynamic Comfort in the Previous Works

Many studies dealing with the dynamic comfort of a seat have been made. Most of them have considered the vibration transmissibility curve to be very important. In particular, they have utilized the resonance frequency and maximum vibration transmissibility of the system consisting of the human body and the seat as a tool for the evaluation of the comfort level of a seat. Not only the study performed by Vartersian (1977, 1982) mentioned previously, but also the studies by Cavender and Kinkelaar (1996) and Crocco and Kinkelaar (1998) indicated that the dynamic comfort of a seat was improved when the vibration transmissibility at resonance frequency (maximum vibration transmissibility) was lowered. Such finding has already been reflected in the test standards of related industries. The JASO standard (1987), which is the Japanese standard for automobiles, treats the resonance frequency and transmissibility of a seat as one of the items for the evaluation of the comfort level of a seat. Most of seat manufacturers perform similar testing.

It can be said that such an evaluation method that treats the maximum vibration transmissibility as an important design parameter has been successfully applied to a general vibration system. However, in the input signal exciting the corresponding system, if the magnitude of vibration that excites the system resonance frequency is very small, it is actually meaningless to lower the transmissibility at resonance frequency. In fact, it was found that under the driving environment of general automobiles, vibration in the vicinity of 5 Hz corresponding to the resonance frequency of the seat-human body system was rarely generated. This matter is described in the following section.

3. THE CHARACTERISTICS OF VIBRATION TRANSMITTED TO THE SEAT UNDER THE DRIVING ENVIRONMENT

In this section, an attempt has been made to examine the influence on the vibration characteristics of the seat-human body system by the input signal of the seat-human body system. This has been done by measuring and

Table 1. Condition for the measurement of seat support vibration of a driving vehicle.

Type of road	Driving road	Vehicle	Speed
Special road	Belgian road	A	40 km/h
		B	60 km/h
General road	Coarse asphalt	A,B,C	60 km/h
	Rough concrete	D, E	30, 50 km/h
	Smooth asphalt		70, 90 km/h

analyzing the vibration transmitted to the seat support from the chassis of an actual vehicle in motion.

3.1. Measurement and Analysis of Vibration Transmitted to the Seat

3.1.1. Conditions for vibration measurement

Vibration occurring at the seat rail, which supports the seat, was measured for various vehicles while running on both special and general road surfaces. The measurement conditions are shown in Table 1.

A Belgian road having a singular type of road surface was one of the roads used to test the vehicle for its characteristics in the course of developing a new vehicle. It was selected for the test because it was expected that high magnitude vibration with a wide frequency band would be generated due to the characteristics of the road. A general road was also selected because it was thought to have road conditions similar to the actual condition under which many vehicles operate. Also chosen was a coarse asphalt road, having a surface condition similar to that of an asphalt road prior to compacting with a roller after the first layer of pavement is laid. Its surface is coarser than the general type asphalt road. However, it develops various frequency components compared to smooth asphalt. As well, a rough concrete road was also selected since it is a type of road that is used in back streets or as local district roadways. Although it is rarely seen in common cities, it has been selected for the test considering the possibility that it may develop the resonance component of the seat-human body system. Among vehicles A, B, C, D and E in Table 1, vehicles A, B, C and vehicles D and E have a piston displacement of 2000cc.

Vibration was measured at the rear side of the right seat rail of the driver's seat. Acceleration data was recorded for 30 seconds while driving the vehicle at constant speed, and then it was converted into a frequency spectrum. A B&K 4383 accelerometer and a B&K 2635 amplifier were used to measure the acceleration. Since the piezoelectric accelerometer experienced

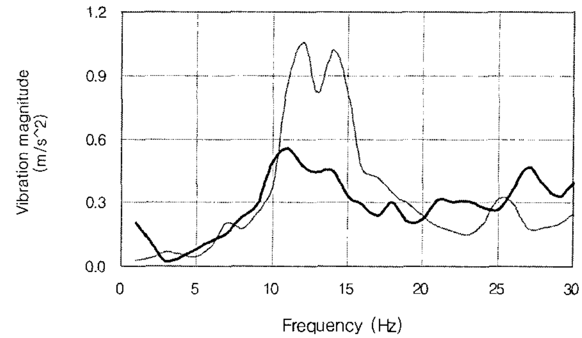

Figure 1. Characteristics of the vibration at the seat installation point under various driving conditions: Vehicle A at 40 km/h (Thick line); and vehicle B at 60 km/h (Thin an dim line) on the Belgian road.

change in the sensitivity below 1 Hz, only the frequency components above 1 Hz are shown in the figure.

3.1.2. Results of vibration measurement

Figure 1 shows the acceleration signal spectrum measured at the seat rail while vehicles A and B were running on the Belgian road at 40 km/h and 60 km/h, respectively. It can be seen from Figure 1 that both vehicles generated high magnitude vibration in the range of 8–20 Hz. It also shows that when vehicle A was running at 40 km/h, the magnitude of vibration increased a little in the vicinity of 1 Hz. However, the vibration magnitude increased greatly above 10 Hz and the vibration magnitude is relatively very low in the vicinity of 5 Hz, where the resonance of the 'seat-human body' system exists.

Figure 2 shows the results of measurement while test vehicles were driving on the general road. When vehicles A, B and C ran on the coarse asphalt road at 60 km/h, the vibration spectrum (Figure 2(a)) indicated that the high vibration magnitude values were concentrated within a 10–15 Hz frequency band. Figures 2(b) and (c) illustrate the vibration spectrum measured at the seat rail when vehicle D and E ran on the asphalt road with a well-paved surface at 90 km/h and 70 km/h and on the rough concrete road at 50 km/h and 30 km/h, respectively. These two figures indicate that when the vehicle ran on the asphalt road at 90 km/h the vibration magnitude corresponding to the primary resonance of the vehicle suspension device was relatively high and the vibration within 10–15 Hz was low. It was also known that the primary resonance component of the suspension device was not shown when vehicles ran on the same road at 70 km/h, however, the frequency components of 10–18 Hz and above increased to a great extent. In Figures 2(b) and (c), it can be seen from the thick and dim line depicting the results when the vehicle ran on the rough concrete road at 30 km/h that the vibration magnitude near 5 Hz

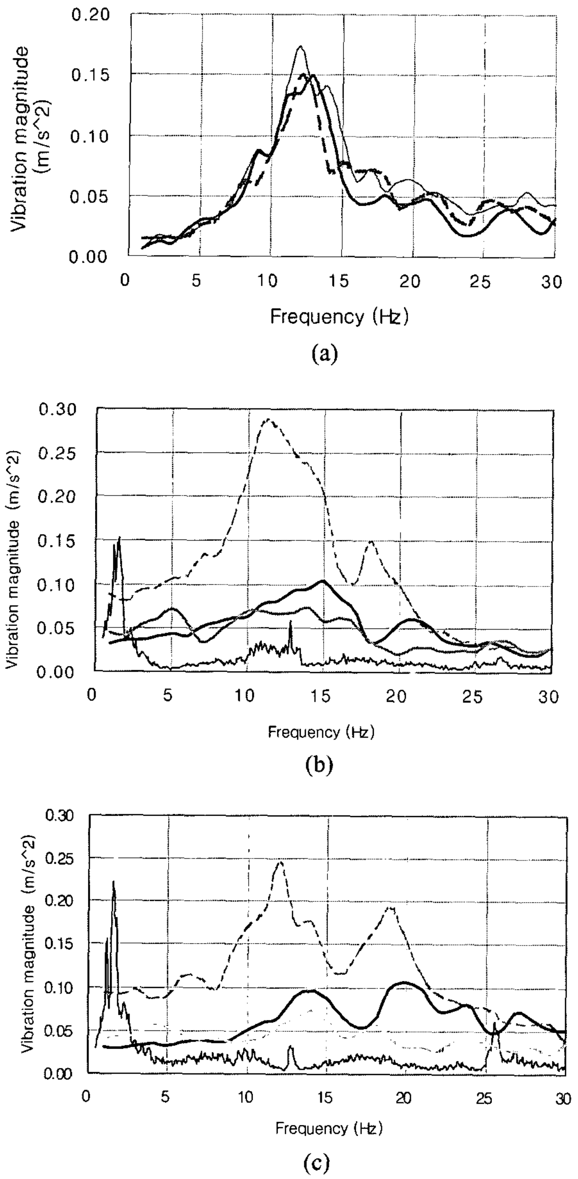

Figure 2. Characteristics of the vibration at the seat installation point under various test conditions: (a) Vehicles A, B and C at 60 km/h on the coarse asphalt road (Thin line: Vehicle A, Thick line: Vehicle B, Thick dashed line: Vehicle C); (b) Vehicles D driving at 90 km/h (Thin line) and 70 km/h (Thick and dark solid line) on the smooth asphalt and at 50 km/h (Thin dashed line) and 30 km/h (Thick and dim solid line) on the rough concrete road; (c) Vehicle E driving at 90 km/h (Thin line) and 70 km/h (Thick and dark solid line) on the smooth asphalt and at 50 km/h (Thin dashed line) and 30 km/h (Thick and dim solid line) on the rough concrete road.

was relatively high and that the vibration magnitude within the 10–15 Hz frequency range was as high as the magnitude near 5 Hz although the magnitude differs depending on the vehicles. This may be due to the fact that when driving on an unevenly surfaced road at low speed, the vibration exciting component generated by the uneven road surface profile was transmitted to the vehicle chassis without being reduced by the suspension device sufficiently. When driving on the rough concrete road at 50 km/h, the vibration magnitude within the 10–15 Hz band rapidly increased while the 5 Hz band reduced relatively.

3.2. Test Result Analysis Considering the Vehicle Characteristics

The analysis results in Figures 1 and 2 may be insufficient to account for all the vehicle-driving conditions. Moreover, since the vibration characteristics of the vehicle chassis varies depending on the driving speed, it is necessary to perform the test at various driving speeds. However, the above test results depict typical vibration characteristics of the chassis of general passenger cars driving on various types of roads at various speeds. Therefore, from the results of tests performed in this study, it is possible to derive the following conclusions:

First, the primary resonance component with frequency close to 1 Hz of the vehicle suspension device was generated when the vehicle ran on the smooth surface road at high speed. It seems that this was generated due to the vibration component having an long wavelength generated from the road. It was found that the frequency component within 10–15 Hz relating to the secondary resonance of the vehicle suspension device and engine mounting frequency was generated obviously under all driving test conditions. The vibration component having a frequency near 5 Hz where the resonance frequency of the system comprised of both seat and human body was rarely generated when driving on the well paved freeways or national highways. Alternatively, it was frequently generated when driving on the roads with uneven surfaces at low speed. However, vehicles rarely drive on such roads and if they do, it is usually for a limited period of time.

3.3. Improvement of the Method for Evaluating Dynamic Comfort of a Seat

This study examined whether it is necessary to seriously consider the transmissibility of vibration having a frequency near 5 Hz where the resonance of the seat-human body system exists when evaluating the dynamic comfort level of vehicle seating. It can be seen from the measurement results of the above driving tests that, except for the case of driving on the rough concrete road at low speed, the vibration magnitude near the frequency of 5 Hz was relatively very low. Such tendency results from the structural characteristics of general passenger cars, which

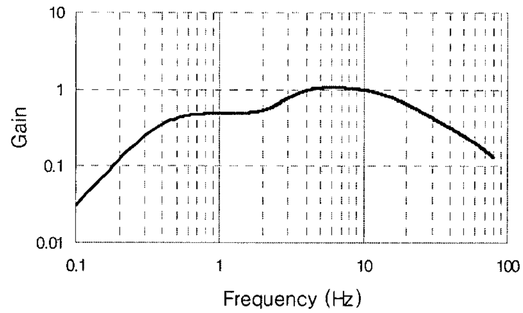

Figure 3. Frequency weighting for the evaluation of human response to vertical vibration of a seated human body.

signify that the primary and secondary resonance frequencies are slightly higher than 1 Hz and 10 Hz, respectively. It is inevitable that the vibration component with a frequency near to 5 Hz (which is 4–5 times as high as the primary resonance frequency), where the resonance frequency of the seat-human body system exists, becomes very low. Actually, this can be the reason that the resonance frequency of the seat-human body system is approximately 5 Hz.

In order to evaluate the dynamic comfort of a vehicle seat under a driving environment, this study proposes to use the vibration transmissibility with its frequency in the range of 10–18 Hz as a base for seat comfort evaluation instead of utilizing resonance frequency or maximum vibration transmissibility. The sensitivity of the human body to the vibration frequency shall be considered in determining the frequency component of certain bands as an object for vibration reduction. For general passenger cars, in order to cover the frequency band where the second resonance of the suspension device and the engine mounting frequency exist, it is necessary to consider the frequency component of and above 10 Hz. The difficulty lies in determining the upper bound of frequency range to be considered. The sensitivity of the seated human body to vertical vibration is determined using the frequency-weighting factor in Figure 3 as proposed by ISO 2631-1. The frequency range where the gain becomes 0.7 is 3–18 Hz. In order to improve the dynamic comfort level of seating, focus shall be placed on reducing the vibration magnitude in this range. In the case of actual vehicles, the frequency component above 18 Hz is frequently generated. However, since its sensitivity decreases due to the characteristics of the human body, the design policy is to reduce the magnitude by up to 10–18 Hz.

4. IMPROVEMENT OF DYNAMIC COMFORT THROUGH DAMPING REDUCTION OF A SEAT

This study attempts to analyze the vibration damping effect by applying the method to reduce the damping capacity of the seat foam to an actual vehicle in order to obtain the vibration reduction in the frequency range of 10–18 Hz.

4.1. Ground for Reduction of Damping Capacity of Seat Foam

As can be seen from the study performed by Cho (2000), the characteristics of the frequency transmission function of the system comprising seat and human body peak around 5 Hz with only very limited peak above 10 Hz. Of course, this system includes non-linear characteristics. However, the behavior of this system is similar to the one degree-of-freedom vibration system within a certain input range. In this study, the concept of the one degree-of-freedom vibration system is utilized in order to explain the effect by damping reduction of the foam. When representing the seat-human body as a one degree-of-freedom system, the human body corresponds mass and the seat to spring and damping, respectively.

Figure 4 depicts the vibration transmission characteristics curve of the one degree-of-freedom vibration system to which base motion is input. The resonance frequency of this system is 5 Hz and its vibration attenuation range exists above 7 Hz. As can be seen from Figure 4, if system damping is increased, transmissibility decreases in the resonance range (A range), but vibration transmission increases above the resonance range (B range). Conversely, if system damping is reduced, the maximum vibration transmissibility increases, but the vibration transmission decreases in the B range. Therefore, if the seat damping is reduced under the vehicle environment where the vibration of B range is generated, it is expected that it will actually reduce the vibration transmitted to the human body.

In this study, as an effective means to reduce seat damping, the damping by seat foam was reduced by 33% as compared to existing products. For reference, the low damping foam used in this study is a type of high-

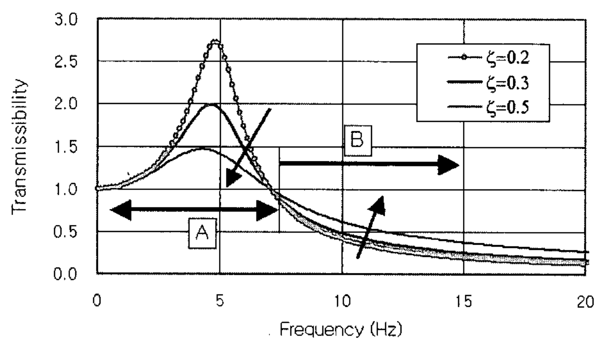

Figure 4. Vibration transmissibility of the one degree-of-freedom system under various damping conditions (Two arrows indicate the increase of damping).

resilience (HR) foam widely used by vehicle industries in advanced countries including Japan for the improvement of seat comfort. It has the advantage of being able to reduce the damping value without impacting the basic static characteristics of the seat.

4.2. Test and Performance Evaluation for the Improved Seat

4.2.1. Comparison using vibration transmissibility of the seat

For the seat test, two types of seats were used, the existing type of seat and another type comprised of improved seat foam. Both types were installed in the test vehicle with a displacement of 2000 ml. With the seats being installed in the same vehicle in turn, the vibration isolation characteristics of the two seats were compared for two types of driving conditions. For these conditions, two types of roads with rough concrete pavement on which the vehicle ran at 50 km/h and asphalt pavement on which vehicle ran at 90 km/h were selected from among those in the above Section 3. A vehicle different from the one used in the above Section 3 was used for the test. The vibration transmission performance of the seat was evaluated by obtaining the transmissibility between the vertical acceleration measured at the seat rail and the acceleration measured with the seat pad accelerometer installed between the seat and the hip of the driver.

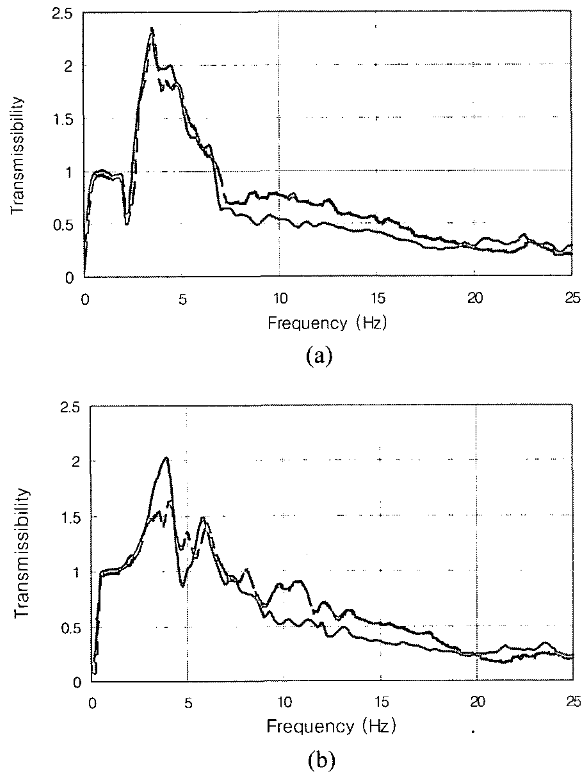

Figure 5. Comparison of vibration transmissibility of the original seat and the modified seat with lowered damping coefficient of 33% under two types of test conditions: (a) Driving at 50 km/h on the rough concrete road (dashed line: Original seat, Solid line: Modified seat); (b) Driving at 90 km/h on the asphalt road (dashed line: Original seat, Solid line: Modified seat).

Figure 5 shows the evaluation results. Figures 5(a) and (b) indicate the vibration transmissibility when the test vehicle ran on the rough concrete road at 50 km/h and on the asphalt road at 90 km/h, respectively. The dotted line and full line specify the results of the test performed for the existing seat and the seat containing the damping reduced foam, respectively.

The significant point of the transmissibility curve in the above two test conditions is that the vibration attenuation performance was improved in the frequency range above 7 Hz when the damping capacity was reduced. Figure 5(a) shows that the transmissibility at 10 Hz was improved from 0.77 to 0.54 while Figure 5(b) indicates that it was improved from 0.83 to 0.56. Each is an about 30% improvement in the transmissibility. However, It can be seen from Figure 5(b) that the maximum vibration transmissibility increased by approximately 25% from 1.6 to 2.0. A specific critical transmissibility value at resonance frequency has not yet been defined. However, if maximum transmissibility is less than 3, corresponding industries consider it acceptable. Generally, it falls between 2.5 and 3. Therefore, it can be said that the increase in the maximum vibration transmissibility as shown in the test results is not so much as to create any problem. In both of the two transmissibility function curves, the characteristic curves in the vicinity of resonance frequency are in the instable form. It can be inferred that the vibration transmitted to the seat support point in the corresponding frequency range is too small. That is, the S/N (Signal to Noise) ratio is very small.

As can be seen from the above figures, transmissibility increased in the resonance range and decreased above the resonance range. In order to examine what impact these results had on the dynamic comfort of a driver, the effect of seat improvement was evaluated by obtaining the vibration transmission rate of the seat, that is, the SEAT

Table 2. SEAT values of the two seats at the two test conditions.

Seat \ Test condition	50 km/h on the rough concrete road	90 km/h on the asphalt road
Original seat	0.88	0.88
Modified seat	0.78	0.77

value considering the perception characteristics of the human body. Using equation (2) the SEAT values for seats before and after the improvement under two driving conditions were calculated and shown in Table 2.

The second and third columns of Table 2 show the SEAT value for the existing seat and the improved seat, respectively, indicating that the SEAT values were reduced by 11% and 12% under two driving conditions. As can be seen from Figure 5(b), the SEAT value was decreased despite the increase in the vibration magnitude. This is thought to be due to the fact that the magnitude of vibration with frequency concentrated on the attenuation range (B range in Figure 4) was reduced to a greater extent than the increase in the vibration magnitude in the resonance range (A range in Figure 4) while the sensitivity of the human body to vibration was maintained high in the frequency range of approximately 3–18 Hz.

4.2.2. Subjective evalaution of dynamic comfort of the improved seat

Six subjects with more than three years' experience on seat performance evaluation joined the test. Each subject was asked to judge dynamic comfort of a seat, i.e., vibration transmission through buttock. In the test, dynamic comfort of a seat was evaluated using an ordinal scale. Integers one to five were assigned to poor, fair, good, very good, and excellent, respectively. After driving a vehicle with the orginal seat and the modified seat successively, subjects rated dynamic comfort of the two seats.

Median values of the 6 subjective rating scores on dynamic comfort or vibration transmission for each of the two seats, the original one and the improve one, were 2.8 and 3.6. This shows the subjects judged the vibration transmission of the improved seat was reduced. It means the improved seat showed better dynamic comfort, which coincided the results by the objective measurement of Section 4.2.1.

5. CONCLUSIONS AND DISCUSSION

This study proposes a new design guideline for the evaluation of the dynamic comfort level of vehicle seating, which proclaims that the factors for seat design should be determined so that the transmissibility of vibration having a 10–18 Hz frequency band can be reduced. For this purpose, this study attempted to improve the dynamic comfort of seating by reducing the damping capacity of the seat, and verified this effect experimentally. Foam with low damping capacity was constructed and installed in a vehicle and seat performance improvement was then analyzed and compared with the performance of the existing seat. The analysis result indicated that the maximum vibration transmissibility of the seat-human body system was increased, but the vibration attenuation characteristics in the frequency range above the resonance range was improved. It also demonstrated that the seat dynamic comfort was improved by approximately 11% upon comparison using SEAT value, which is the vibration transmissibility of a seat that considers the perception characteristics of the human body. The improvement of the dynamic comfort was also verified through the subjective assessment.

This study proposes the method to improve the seat performance focusing on the improvement of its dynamic comfort. The comfort of a seat is greatly influenced by the dynamic characteristics as well as the static characteristics. Therefore, the improvement of the comfort level shall be evaluated using various design factors (Jang, 2001). However, since the high resilience (low damping) foam that is widely used for seating has higher modulus of elasticity than existing foam, it not only provides a superior sitting feeling, but also improves the dynamic comfort of a seat because of its low damping capacity as demonstrated by this study. In this study the static comfort of a seat is not mentioned separately because it does not decrease even though foam having a low damping capacity has been used. This study attempts to analyze the vibration damping effect by applying the method to reduce the damping.

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