RESEARCH ON THE RELATIONSHIP BETWEEN RIDING COMFORT AND CAR SEAT MATERIALS

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The relationship between riding comfort and the properties of flexible polyurethane foam used in car seats was quantitatively illustrated through vibration experiments with humans sitting in car seats, which were vertically shaken by vibrator. Riding comfort was estimated according to SD (Semantic Differential)-method using questionnaire, and was analyzed with a factor analysis which demonstrated the principal factors of riding comfort. At the same time, riding comfort was related to the properties of the flexible polyurethane foam with coefficients of correlation. It was also related to the behaviour of its vibration of humans sitting in the seats. As a result, it was demonstrated that the relationship between riding comfort and the flexible polyurethane foam properties varies according to the frequency of the vibration shaking the human sitting in the seat. And it was demonstrated that the frequency dependence of the relationship is strongly affected by the physical changes of the vibration modes of the human-seat vibration system.

Introduction

Recently, the demand for performance of car seats has rapidly changed with the improvement in in-car comfort and the lowering of costs, etc. For example, recent developments in car seats have tended to reduce their thickness to obtain more headroom, and to remove spring elements to reduce costs. Flexible polyurethane foam has been evaluated as the most suitable material for car seat production. Seats made of flexible polyurethane foam can have simpler structures and can be reduced in size. Moreover, the physical and chemical properties of the foam can be easily changed, so that a desirable riding comfort can be achieved with its use. There are no case studies which investigate the relationship between riding comfort and the properties of flexible polyurethane foam. However, there are many case studies which investigate the relationship between the result of sensory evaluation of comfort and pressure on the human body caused by seats, and between the resulting comfort and sitting posture[1-3]. Additionally, comfort evaluation according to the human framework configuration and the physiological response has been carried out[4-6].

2. Materials and Methods

2.1. Properties of experimental seat cushions

The material properties of five experimental seat cushions made of five different flexible polyurethane foams were measured according to JIS[7] and JASO[8]. Furthermore, the viscoelastic properties of the foam were also measured with DMA (Dynamic Mechanical Analysis).

2.2. Experimental devices

The Itoseiki-built seat cushion vibrator (C-1002DL) was used to impose vertical sinusoidal vibration on the subjects, as described later. The real car seat, with only the seat cushion of the seat pan removed was fixed on the vibrator. Each experimental seat cushion was installed in the car seat, to comparatively evaluate the

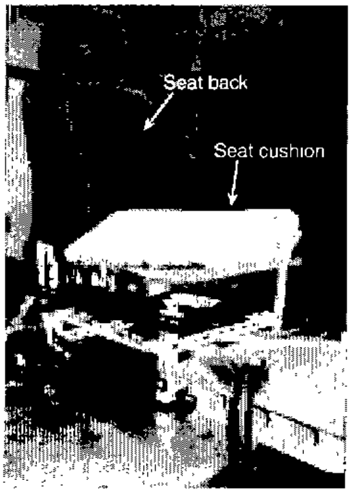


Fig.1. Real car seat fixed on a vibrator

Fig.2. Subject sitting in car seat

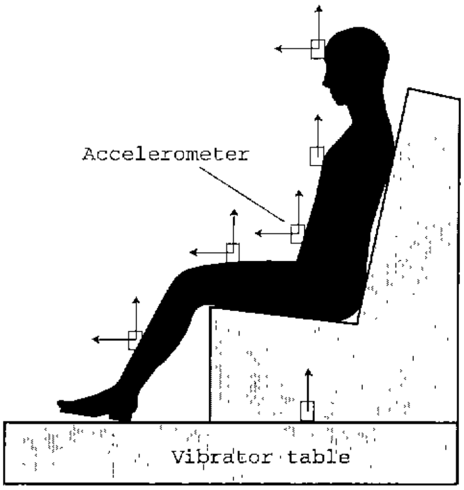


Fig.3. Mounting positions of accelerometers

sensory difference between the experimental seat cushions (Fig.1). Additionally, the seat cushions were installed without seat fabric to avoid influences of tension induced by the fabric.

2.3. Experimental subjects and sensors

17 subjects were used. They were 15 male and 2 female regular car drivers. And 6 subjects selected were equipped with 10 accelerometers (Kyouwadengyo-built, AS-2TG) on the body parts shown in Fig.2, 3, to measure the transmission of human body vibration induced by the vibrator. The accelerations collected by the accelerometers were analyzed with FFT (Fast Fourier Transform analyzer, Onosokki-buit, CF-360) to calculate the transmission. The subjects sitting in the seats were exposed to sinusoidal vibration at the frequencies of 2Hz, 4Hz, 6Hz and 8Hz. The amplitudes of the vibration of each frequency were limited to gravitational acceleration multiplied by 0.1.

2.4. Method for evaluating riding comfort

The subjects evaluated riding comfort during exposure to the vibration according to SD-method. The evaluation consisted of [the feeling of stability], [the feeling of spring], [the feeling of sinking], [the feeling of oscillating], [the feeling of damping], [the feeling of reaching bottom], and [the synthetic comfort]. Each feeling and the synthetic comfort were evaluated on a 7-point scale using questionnaires.

2.5. Method for analyzing riding comfort

In order to clarify how riding comfort consists of the above-mentioned feelings, the principal axes of the vector space illustrated by the average feelings of the 17 subjects were deduced according to a factor analysis. And the relation between each feeling and each physical property of the seat cushions was calculated with coefficients of correlation, to investigate the properties' affect on riding comfort.

2.6. Modal analysis of human-seat vibration system

The dynamic characteristics of the human-seat vibration system, by which subjects sitting in seats are vibrated by the vibrator, were investigated with a modal analysis. The modal analysis was carried out using a FEM (Finite Element Method) -application (ANSYS Ver.5.5), to clarify the inherent characteristics of the vibration system. The human body, seat and seat cushions were numerically modelled according to FEM, with the physical data measured during the preparatory experiments.

3. Results

3.1. Result of evaluation of the feelings

Table 1 shows the average feelings in each experimental seat cushion at every frequency of the vibration shaking the human and seat. Figure 4 describes how the feelings vary according to the frequency of the vibration. As a result, it was clear that the maximum or minimum value of each feeling exists at 4Hz. In particular, the minimum values of the feeling of stability and synthetic comfort, and the maximum value of the feeling of spring and oscillating could be clearly

Table 1. Averaged feelings evaluated by the subjects

Sample		A	B	C	D	E
2Hz	Feeling of stability	4.71	3.53	4.00	5.29	5.12
	Feeling of spring	3.65	3.82	3.41	3.41	3.41
	Feeling of sinking	4.35	5.12	5.06	3.35	4.18
	Feeling of oscillating	3.12	3.94	3.82	2.88	2.94
	Feeling of damping	3.41	3.94	3.88	4.29	3.65
	Feeling of reaching bottom	3.06	4.06	4.06	2.47	3.06
	Synthetic comfort	4.18	3.47	4.06	5.29	4.59
4Hz	Feeling of stability	2.47	1.76	2.88	3.35	2.82
	Feeling of spring	5.76	4.88	4.71	5.06	4.65
	Feeling of sinking	4.94	4.82	5.06	3.82	4.41
	Feeling of oscillating	5.12	5.00	5.00	4.00	4.71
	Feeling of damping	2.71	2.88	3.76	3.65	3.76
	Feeling of reaching bottom	3.18	4.59	4.06	2.82	3.29
	Synthetic comfort	2.41	1.88	2.24	2.88	2.88
6Hz	Feeling of stability	3.94	3.12	3.29	3.94	3.71
	Feeling of spring	4.47	4.59	4.18	4.47	4.24
	Feeling of sinking	3.59	4.18	3.88	2.88	3.71
	Feeling of oscillating	3.88	4.06	4.12	4.00	3.82
	Feeling of damping	3.65	2.94	3.88	4.00	3.65
	Feeling of reaching bottom	2.59	3.53	3.35	2.65	3.00
	Synthetic comfort	3.82	3.06	3.29	3.53	3.53
8Hz	Feeling of stability	5.24	4.65	4.76	5.00	4.76
	Feeling of spring	3.41	3.47	3.12	3.24	3.00
	Feeling of sinking	2.94	3.00	3.12	2.41	2.88
	Feeling of oscillating	3.12	3.12	2.88	2.76	2.76
	Feeling of damping	3.71	3.65	4.53	4.18	4.12
	Feeling of reaching bottom	2.18	3.12	2.71	2.24	2.41
	Synthetic comfort	4.76	4.12	4.53	4.71	4.59

Table 2. Factors illustrating riding comfort

	Factor 1	Factor 2
Feeling of spring	0.965	-0.153
Synthetic comfort	-0.849	0.470
Feeling of oscillating	0.834	-0.485
Feeling of stability	-0.823	0.506
Feeling of damping	-0.741	0.247
Feeling of reaching bottom	0.271	-0.938
Feeling of sinking	0.340	-0.878
Eigenvalue	5.3	0.9
Proportion	75.8	12.9
Cumulative	75.8	88.7

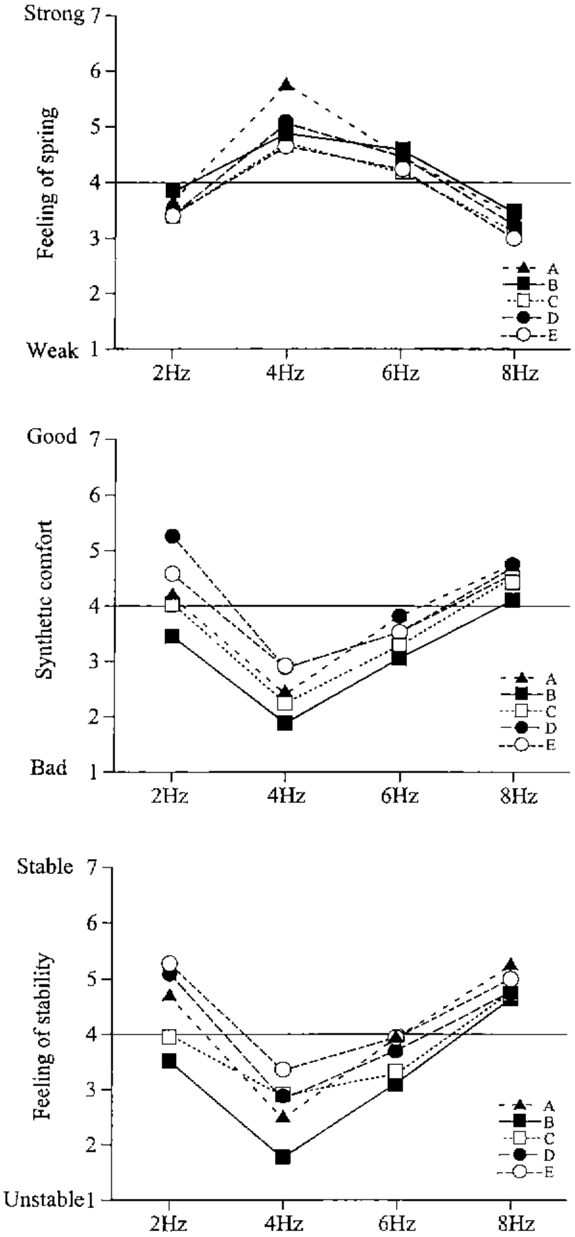


Fig.4. Variations in the feelings according to the frequency

sighted. Additionally, the ranking of the experimental seat cushions in all vertical axes of Figure 4 almost agrees with that of the synthetic comfort, suggesting that there was a close relation between the feelings and the synthetic comfort. For example, at 4Hz the feeling of stability decreased, and the feeling of spring and oscillating increased, so that synthetic comfort was at its worst.

3.2. The factors for evaluating riding comfort

The evaluation factors illustrated how riding comfort consists of the above-mentioned feelings. Table 2 shows the quantities of factor loading, eigenvalues, and cumulative rates of the contribution. All the values in Table 2 relate to the rotated factor pattern. As a result, it was demonstrated that riding comfort could be illustrated by two factors. One factor being the feeling of spring, the synthetic comfort, the feelings of oscillating, stability, and damping, and the other being the feelings of reaching bottom and sinking. Furthermore, it was suggested that synthetic comfort would increase when feelings of spring and oscillating are weak, and when feelings of stability and damping are strong.

Table 3. Transmissibility of the vertical vibration

	Sample	A	B	C	D	E
Head	2Hz	1.32	1.32	1.28	1.26	1.27
	4Hz	3.77	3.79	3.88	3.37	3.46
	6Hz	1.13	1.17	1.36	1.23	1.21
	8Hz	1.13	1.09	1.14	1.14	1.20
Chest	2Hz	1.27	1.29	1.24	1.18	1.21
	4Hz	3.57	3.80	3.21	2.71	2.88
	6Hz	2.14	2.11	2.01	2.54	2.44
	8Hz	1.05	0.96	1.02	1.35	1.31
Abdomen	2Hz	1.21	1.25	1.21	1.15	1.17
	4Hz	3.43	3.57	3.19	2.63	2.66
	6Hz	1.94	1.81	1.80	2.12	1.99
	8Hz	1.43	1.28	1.21	1.76	1.63
Thigh	2Hz	1.18	1.17	1.17	1.12	1.13
	4Hz	2.63	2.62	2.43	2.06	2.18
	6Hz	1.56	1.58	1.39	2.18	1.88
	8Hz	1.90	1.76	1.94	2.31	2.13
Lower leg	2Hz	1.05	1.04	1.03	1.03	1.04
	4Hz	1.40	1.33	1.32	1.35	1.46
	6Hz	1.22	1.22	1.23	1.19	1.34
	8Hz	1.69	1.63	1.51	1.45	1.68

Table 4. Transmissibility of the horizontal vibration

	Sample	A	B	C	D	E
Head	2Hz	0.31	0.57	0.45	0.34	0.35
	4Hz	0.93	0.97	0.86	0.80	0.65
	6Hz	0.52	0.48	0.48	0.59	0.55
	8Hz	0.21	0.21	0.20	0.21	0.20
Abdomen	2Hz	0.17	0.07	0.13	0.08	0.07
	4Hz	0.99	0.85	0.68	0.66	0.65
	6Hz	0.87	0.84	0.83	1.45	1.18
	8Hz	0.63	0.57	0.60	1.01	0.85
Thigh	2Hz	0.06	0.26	0.25	0.06	0.11
	4Hz	1.65	1.79	1.47	0.82	1.03
	6Hz	1.57	1.69	1.70	1.44	1.61
	8Hz	1.54	1.46	1.60	1.47	1.59
Lower leg	2Hz	0.14	0.13	0.01	0.14	0.07
	4Hz	0.63	0.92	0.85	0.25	0.73
	6Hz	0.71	0.87	0.93	0.80	0.76
	8Hz	0.82	0.89	0.91	1.13	0.81

3.3. Result of transmissibility of human body

Table 3 and 4 shows the average transmissibility of the vertical and horizontal vibration of each part of the human body, namely the head, chest, abdomen, thigh and lower leg. The average transmissibility was illustrated at each seat cushion. Vertical transmissibility was only measured at the chest because it was clear that the horizontal transmissibility was weak so that its effect could be disregarded. And the transmissibility of the lower leg was measured on one subject, so that the standard deviation of transmissibility could not be calculated. The transfer characteristics of the vibration at each frequency were as follows:-

1) The transfer characteristic at 2Hz

The vertical transmissibility of each part of the body was close to 1, while the horizontal transmissibility was close to 0 except in the case of the head. Thus the human body sitting in the seat vibrated in a vertical direction with the same amplitude as the vibrator, and each part of the human body vibrated less in a horizontal direction at 2Hz.

2) The transfer characteristic at 4Hz

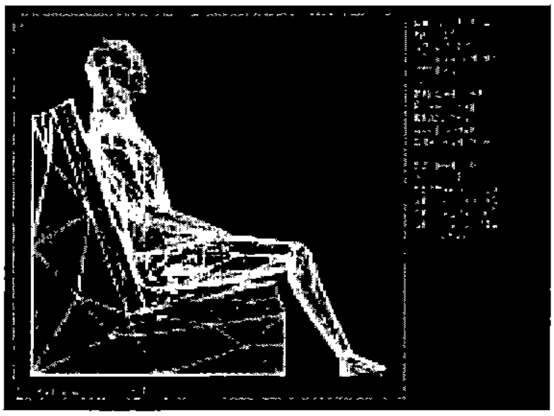
The transmissibility of each part of the body increased compared with the transmissibility at 2Hz. In particular, the vertical transmissibility of the head, chest and abdomen increased dramatically, and it was verified that the transmissibility peaked at 4Hz. This suggests that there was a resonance frequency at around 4Hz, at which the upper half of the human body vibrated violently.

3) The transfer characteristic at 6 and 8Hz

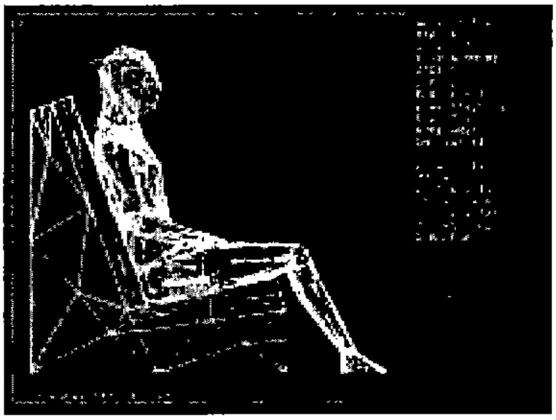
Although the transmissibility of both vertical and horizontal vibrations of the head, chest and abdomen decreased in comparison with the transmissibility at 4Hz, the transmissibility of the thigh and lower leg increased at 6 and 8Hz. Furthermore, it was verified that the horizontal transmissibility of the thigh and lower leg was almost equal to its vertical transmissibility at 6 and 8Hz. It was therefore possible to predict that there would be an essential difference between the vibration characteristics at 2 and 4Hz and those at 6 and 8Hz.

3.4. Result of the modal analysis of the human-seat vibration system

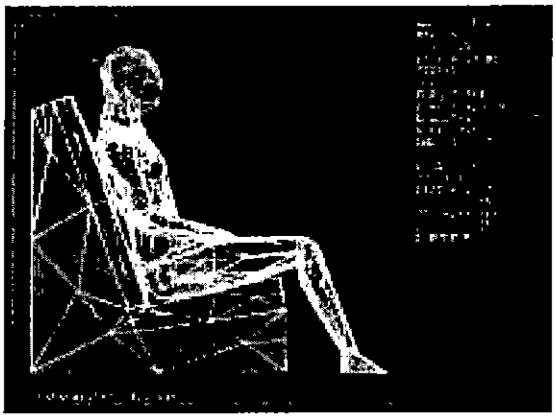
From the modal analysis of the human-seat vibration system, it was shown that the lowest characteristic frequency was 4.78Hz and the natural vibration mode relating to its frequency showed strong vertical vibration (Fig.5). This suggested that the real human-seat vibration system would show clear vertical vibration at around 4 to 5Hz. This result almost conforms to the experimental one, in which the resonance frequency induced by the external vertical sinusoidal vibration was at around 4Hz. Also, the second and third characteristic frequencies were 6.60Hz and 7.76Hz, respectively. The natural vibration modes relating to both frequencies show strong horizontal vibration as compared with the eigenvector of the lowest characteristic frequency: 4.78Hz (Fig.5). This suggests that the real human-seat vibration system would clearly show both



a) 4.78Hz



b) 6.60Hz



c) 7.76Hz

Fig.5. Natural vibration modes of the human-seat system

horizontal and vertical vibration at around 6 to 8Hz. This result conforms with the experimental ones at 6 and 8Hz.

Table 5 Coefficients of correlation between riding comfort and the properties of flexible polyurethane foam

	2Hz	4Hz	6Hz	8Hz
Over-all Density	-0.841	**-0.896**	-0.268	-0.390
Ball rebound	**-0.886**	**-0.918**	-0.280	-0.456
Air flow ability	-0.457	-0.460	0.167	-0.194
Hardness·25%ILD	0.530	0.378	0.739	0.674
Stress relaxation	**0.892**	**0.889**	0.253	0.417
Ratio of hysteresis loss	0.747	0.800	0.059	0.217
Quantity of elastic hysteresis loss	0.857	0.873	0.251	0.373
Deflection - 500N	-0.874	-0.843	-0.743	-0.746
Deflection - 40N	-0.859	-0.700	-0.610	-0.682
Spring constant - 500N	-0.823	-0.670	-0.535	-0.573
Spring constant - 200N	0.759	0.732	0.599	0.532
Spring constant - 40N	0.817	0.655	0.617	0.662
Ratio of spring constant	0.876	0.765	0.591	0.635
Compressibility	**-0.916**	-0.834	-0.645	-0.703
Resonance frequency	0.553	0.612	-0.201	0.054
Transmissibility at peak	-0.220	-0.307	0.179	-0.124
Transmissibility at 6Hz	0.491	0.528	-0.153	0.181
E' - 2Hz	0.776	0.851	0.139	0.316
E' - 4Hz	0.781	0.855	0.146	0.321
E' - 6Hz	0.786	0.858	0.151	0.326
E' - 8Hz	0.788	0.859	0.153	0.327
E" - 2Hz	**0.881**	**0.894**	0.269	0.413
E" - 4Hz	**0.883**	**0.896**	0.266	0.417
E" - 6Hz	0.867	**0.892**	0.260	0.399
E" - 8Hz	**0.881**	**0.889**	0.262	0.408
Compression-tan δ - 2Hz	0.857	**0.890**	0.238	0.387
Compression-tan δ - 4Hz	0.844	**0.889**	0.235	0.380
Compression-tan δ - 6Hz	0.855	**0.892**	0.239	0.390
Compression-tan δ - 8Hz	0.855	**0.892**	0.242	0.389
G' - 2Hz	**0.922**	0.859	0.255	0.437
G' - 4Hz	**0.923**	0.860	0.257	0.439
G' - 6Hz	**0.924**	0.862	0.264	0.443
G' - 8Hz	**0.924**	0.864	0.265	0.444
G" - 2Hz	**0.927**	**0.879**	0.302	0.463
G" - 4Hz	**0.931**	**0.887**	0.322	0.478
G" - 6Hz	**0.929**	**0.885**	0.321	0.474
G" - 8Hz	**0.933**	**0.883**	0.298	0.472
Shearing-tan δ - 2Hz	0.707	0.826	0.759	0.646
Shearing-tan δ - 4Hz	0.637	0.770	0.859	0.715
Shearing-tan δ - 6Hz	0.595	0.730	0.814	0.642
Shearing-tan δ - 8Hz	0.744	0.877	**0.905**	**0.917**

3.5. Correlation between riding comfort and the properties of flexible polyurethane foam

Table 5 shows coefficients of correlation between riding comfort and the properties of flexible polyurethane foam used in the seat cushions. Boldfaced letters in Table 5 are coefficients of correlation whose significant levels are larger than 5%. It was thus demonstrated that, at 2 and 4Hz, riding comfort was affected by stress relaxation, compressibility, compression-tan δ in a vertical direction, the imaginary parts of each complex elastic modulus at every frequency of vibration and each complex sharing elastic modulus. Here, compression-tan δ is an index representing the vibration damping in a vertical direction. On the other hand, it was demonstrated that riding comfort at 6 and 8Hz was affected only by sharing-tan δ . Here, shearing-tan δ is also an index representing the vibration damping in a horizontal direction. It was thus possible to summarize that riding comfort at 2 and 4Hz relates to the properties of the cushions affecting the behaviour of the vibration in a vertical direction, while riding comfort at 6 and 8Hz relates to the properties affecting the vibration behaviour in a horizontal direction. It should be borne in mind also that the human-seat vibration system had a tendency to vertically vibrate at around 4Hz, while the vibration system had a tendency to horizontally vibrate at around 6 and 8Hz. Thus, it was clear that the relationship between riding comfort and the properties of flexible polyurethane foam used in car seat cushion would be strongly affected by the physical vibration modes of the human-seat vibration system.

4. Conclusions

The following information was obtained from this study on the relationship between riding comfort and car seat materials:-

1) the properties of flexible polyurethane foam clearly relating to riding comfort alter according to the frequency of the external vertical vibration,
2) the impact resilience, stress relaxation, and compression-tan δ which are properties affecting the vertical vibration behaviour relate to riding comfort at 2 and 4Hz, and the sharing-tan δ which is a property affecting the horizontal vibration behaviour relates to riding comfort at 6 and 8Hz,
3) the human body sitting in a seat with cushions made of flexible polyurethane foam showed a tendency to vertically vibrate at 2 and 4Hz, and to horizontally vibrate at 6 and 8Hz.

Finally, it was demonstrated that the relationship between riding comfort and the properties of flexible polyurethane foam used in car seats clearly varies according to the physical behaviour of the human-seat vibration system, in which the physical behaviour changes at every frequency of vertical vibration induced through the vibrator.

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