



EFFECTS OF PRELOAD AND VIBRATION MAGNITUDE ON THE DYNAMIC STIFFNESS OF VEHICLE SEAT

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Abstract:

Ride comfort plays important role in designing the vehicle seat and it can be affected by both statics and dynamic factors. The comfort of a seat is mainly contributed by the seat cushion foam and nowadays, the common material used as seat cushion is open celled polyurethane foam. Under dynamic condition, seat dynamic behavior can be evaluated by measuring it's dynamic stiffness. The purpose of this study in this paper was to investigate the seat dynamic stiffness of three different seats from different car models to provide better understanding of how seat is designed and selected. The seats were tested using indenter testing rig at different preloads of 200N, 400N and 600N and subjected to random vibration from 1Hz to 80Hz at 0.4ms^{-2} , 0.8ms^{-2} and 1.2ms^{-2} root means square (r.m.s). It can be observed that the stiffness and damping did not change much with the variation of vibration magnitude. However, the seat stiffness and damping exhibited significant changed as preload increased. The result of this work can provide an insight for engineers and seat designers on how the preload and vibration magnitude can affect the comfort of seat under vibration.

Keywords: human vibration, vehicle seat, dynamic stiffness, ride comfort

1. Introduction

Vehicle ride comfort becomes an important factor for seat designer and automotive manufacturers to provide the best driving experience for the consumers. In automotive industry, the common type of material for seat cushion is made of flexible open cell polyurethane foam (PU) which directly attached to a seat frame without any suspension system[1]. This type of seat is used in passenger and commercial vehicles; thus, the seat foam characteristics will significantly influence the ride comfort [2]. PU foam has complex microstructures which comprising of intercellular network formed during manufacturing process [3]. The microstructures and the base material used during foaming process will determine the mechanical properties of the PU foam. Under increasing load, PU foam exhibits nonlinear elastic response which occurring in three stages: (i)linear elastic region, (ii) plateau region (elastic, plastic), (iii) densification region [4] as shown in Figure 1.

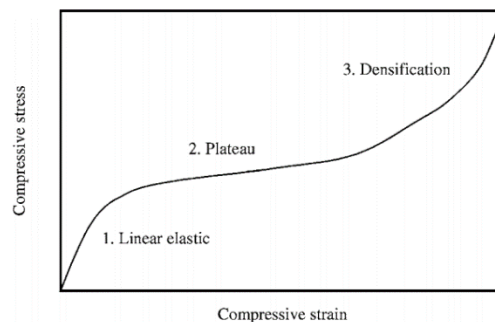


Figure 1: Schematic figure of flexible open cell polyurethane foam under compressive stress-strain [4]

Another factor that plays important role in the vehicle ride comfort is the seat design itself. Seat comfort can be affected by its thickness, density, and its shape in both dynamic and static condition [5], [6]. Seat designers are always playing with firmness and thickness of PU foam to achieve better ride comfort, for instance, if the thickness of cushion is lowered, greater firmness and/or higher density of seat cushion is required to maintain adequate support [7]. Since the seat becomes the component which has direct contact to human body and PU foam as major role in the seat design, it can be stated that seat foam will have large impact on ride comfort. Consideration in both static and dynamic comfort factors are necessary since they will affect the consumer significantly in the long term [2], [5]. Numerous tests have been done by researchers in investigating the factors that affecting the seat comfort [8]. This includes the investigation on both seat cushion at the seat pan and the backrest [6], [9]–[12]. The vibration direction also has been taken into consideration either in the vertical, lateral, and fore and aft direction [6], [13]–[16]. It has been reported that vertical vibration at the seat pan produced most significant effects in comparison

with the other vibration directions [10]. Some researchers have conducted experimental measurement of the seat dynamic stiffness and later, calculated its seat transmissibility [9], [10], [17], [18]. Under increasing load, the dynamic stiffness of PU foam increases, and a similar trend is also observed when using thinner foam [10], [18]. Seat transmissibility also changed with the variation of imposed load or mass [10], [11], [13]. The resonance frequency decreases with the increased of PU foam thickness, however the seat transmissibility amplitude increases with the increased of foam thickness [10], [17], [18]. Researchers also found that seat transmissibility is affected by the variation of vibration magnitude [8]. Under increasing vibration magnitude, the resonance frequency and seat transmissibility amplitude is found to be decreased [19]–[21]. The purpose of this study was to investigate the dynamic stiffness of seats used in several different car models in Malaysia under different preload and vibration magnitude. By comparing the dynamic stiffness, we can understand how difference the seat dynamic stiffnesses between manufacturers, and thus, can be used for better understanding of how seat is designed and selected.

2. Method and Procedure

2.1 Test apparatus and setup

The experiment was conducted using an indenter rig equipped with ETS Solution L215M shaker which has maximum capacity of 70kg and supported frequency of up to 4500Hz as shown in Figure 2. The acceleration on the shaker base was captured using DYTRAN 3522A2 single axis accelerometer which has sensitivity of 99.46 mV/g. Two force sensors were installed in the indenter head mounted on the top part of the indenter rig. The force sensors were used to measure the initial static load applied on the seat as well as during the vibration (dynamic load).

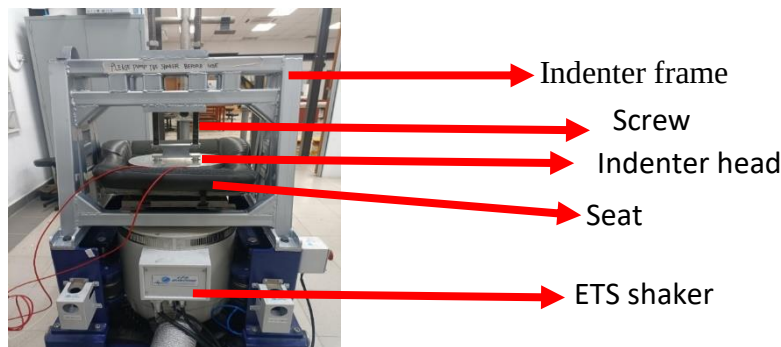


Figure 2: Indenter test rig

The indenter head was designed accordingly as published in a paper [15] with some modifications on fitting for the force sensors as shown in Figure 3. The force sensors used in this study were two FUTEK LTH-350 force sensors which both having a maximum capacity of 500 lb (about 225 kg) and capable to measure static and dynamic load. Both accelerometer and force sensors were connected to National Instrument NI-9324 and NI-0327 data acquisition module, respectively. The signal generation was configured using Siemens LMS Spectral Testing software and acquisition module, while the force and acceleration data were monitored and recorded using LABVIEW software. Post processing of the output data was done using MATLAB.

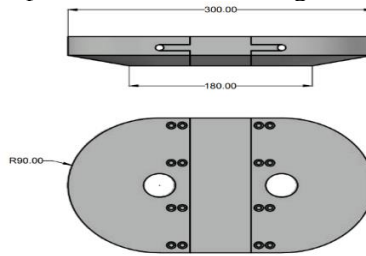


Figure 3: Design of indenter head

2.2 Test sample

Three car seats were employed which came from different car models. The seat foams were disassembled from main frame of driver seat of Proton Exora, Proton Persona and Perodua Kancil as shown in Table 1. These three car models were among the popular vehicles in Malaysia.

Table 1. Seats properties

<i>Parameter</i>	<i>Seat A</i>	<i>Seat B</i>	<i>Seat C</i>
Image			
Density	44 kg/m ³	79.6 kg/m ³	82 kg/m ³
Seat Cover	Fabric	Fabric + leather	Fabric
Dimension	550m x510mm	550mm x 500mm	480mm x 450mm
Car Model	Proton Exora	Proton Persona	Perodua Kancil

2.3 Test procedure

The seat was placed between the indenter head and the shaker test table as shown in Figure 2. The initial static load applied on the seat surface was 200N (20kg). After the preload reached the required amount, the vibration was generated by the shaker. The input vibration was adjusted in LMS software which monitored using LABVIEW. The test was conducted using generated random vibration signal with a frequency range of 1 to 80Hz at three frequencies weighted r.m.s. accelerations of 0.4ms⁻², 0.8ms⁻² and 1.2ms⁻². The measurement was recorded for 60 seconds for each condition with coherency of greater than 0.8 at frequencies greater than 2Hz and a flat power spectral density of the input acceleration. The acceleration data recorded is filtered using Butterworth low-pass filter with cut-off frequency of 50Hz to remove aliasing signal.

3. Result and Discussion

3.1 The dynamic stiffness of the three seat materials

Figure 4 shows the dynamic stiffness of three seat materials at preload force of 200N with vibration magnitude of 0.4 ms⁻². It can be seen that the stiffnesses of the three seats were found to be similar across frequency of vibration from 1 Hz to 20Hz.

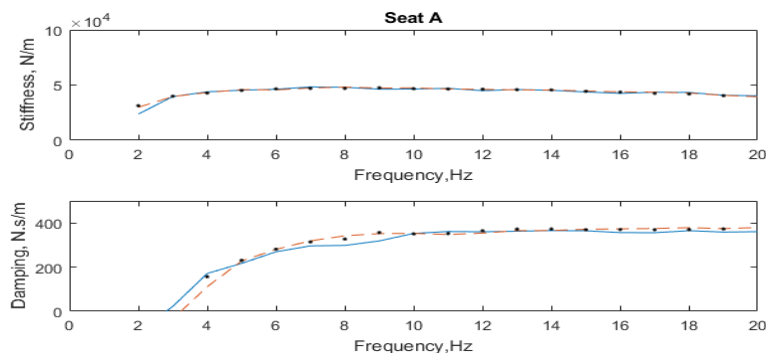


Figure 4: Dynamic stiffness of Seat A under different vibration magnitude of 0.4 ms⁻² (—), 0.8ms⁻² (---) and 1.2ms⁻² (...) at preload of 200N.

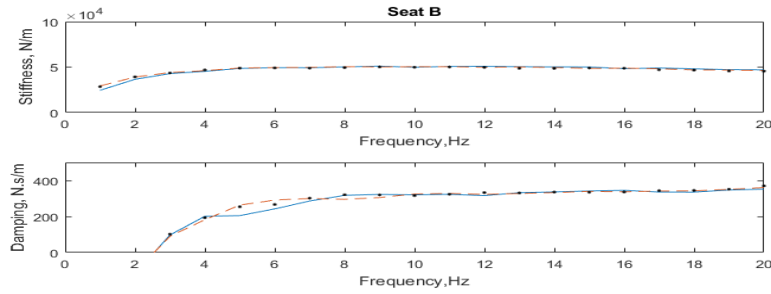


Figure 5: Dynamic stiffness of Seat B under different vibration magnitude of 0.4 ms^{-2} (-), 0.8 ms^{-2} (--) and 1.2 ms^{-2} (...) at preload of 200N.

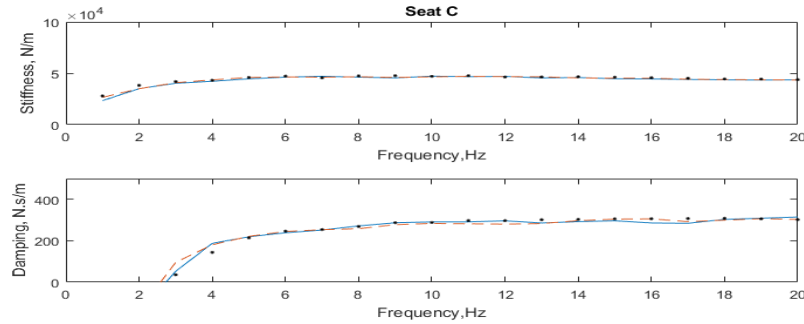


Figure 6: Dynamic stiffness of Seat C under different vibration magnitude of 0.4 ms^{-2} (-), 0.8 ms^{-2} (--) and 1.2 ms^{-2} (...) at preload of 200N.

3.2 Effect vibration magnitude on the dynamic stiffness

Figure 4-6 display the dynamic stiffness of seat material obtained for three seats used in this study with respects to the increased of vibration magnitude. It can be observed that the vibration magnitude has not much affected the stiffness of the seats. Table 2 shows the mean of stiffness of the three seats across frequencies from 2 to 20 Hz at single preload load 200N. All three seats exhibited similar trend and value when vibration magnitude was increased. As the frequency increased, the stiffness trend in flat pattern and does not vary much between each other as seen in the standard deviation. This finding indicates that vibration magnitudes does not has much effect on the stiffness of the seat which is inline with findings obtained by a previous research [7].

Table 2. Effect vibration magnitude on the mean stiffness of seat at preload 200N from 2 to 20 Hz

Seat	Seat A, N/m (mean)		Seat B, N/m (mean)		Seat C, N/m (mean)	
RMS	Mean	SD	Mean	SD	Mean	SD
0.4 ms^{-2}	4.48e4	1.91e4	4.88e4	1.93e4	4.49e4	3.17e4
0.8 ms^{-2}	4.49e4	6.89e3	4.87e4	1.34e4	4.52e4	4.64e4
1.2 ms^{-2}	4.46e4	5.39e3	4.46e4	3.46e3	4.58e4	4.68e4

*SD = Standard deviation

For seat A, the damping at all vibration magnitudes had increased as the frequency of vibration increased up to 20Hz. For Seat B, the damping increased up to 76% across frequency range. Similarly for Seat C, the damping increased by up to 83% across frequency range. The damping for all seats exhibit significant increased for frequency less 5Hz, then moved steadily in slight increased up to 20Hz. However, the damping has no effect towards the increase of vibration magnitude. This result is inline with the findings obtained by a previous research [7].

Table 3: Effect vibration magnitude on the mean damping of seat at preload 200N from 2 to 20 Hz

Seat	Seat A, N/m (mean)		Seat B, N/m (mean)		Seat C, N/m (mean)	
RMS	Mean	SD	Mean	SD	Mean	SD
0.4 ms ⁻²	325.58	58.02	294.39	68.80	261.40	62.73
0.8 ms ⁻²	333.58	69.66	298.48	67.15	262.75	54.42
1.2 ms ⁻²	335.66	60.65	300.35	65.03	262.93	75.73

3.3 Effect preload on the dynamic stiffness

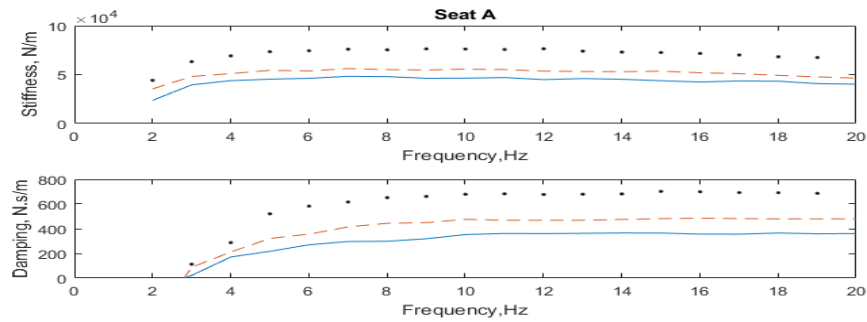


Figure 7: Dynamic stiffness of Seat A, under different vibration magnitude of 200N (-), 400N (--) and 600N (...) at 0.4ms⁻² rms

Figure 7-9 show the effect of preload on the dynamic stiffness at vibration magnitude of 0.4 ms⁻² r.m.s. acceleration. Along the frequency up to 20Hz, the stiffness did not increase or decrease significantly for each preload, but more in a flat trendline, consistent for all seat materials. In contrary, the stiffness did vary significantly as the preload amount changed. As the preload increased, the stiffness of the seat materials increased.

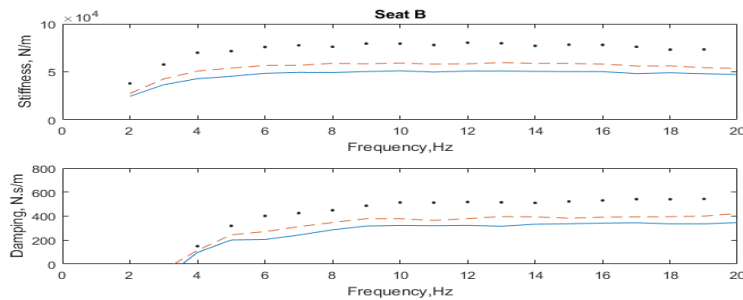


Figure 8: Dynamic stiffness of Seat B, under different vibration magnitude of 200N (-), 400N (--) and 600N (...) at 0.4ms⁻² rms

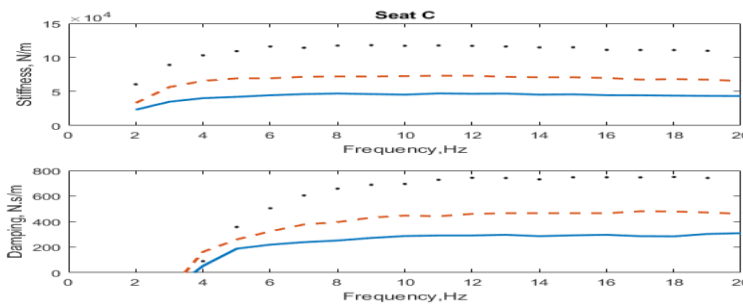


Figure 9 : Dynamic stiffness of Seat C, under different vibration magnitude of 200N (-), 400N (--) and 600N (...) at 0.4ms⁻² rms

The mean values for stiffness of the three seats are shown in Table 2 for frequencies from 2 to 20 Hz. At smaller preload, Seat A produced the lowest stiffness, however when the preload increased to 400N and 600N, Seat C

produced the greatest stiffness compared to the other seats. Increasing stiffness of seat will result in a less comfort to the drivers and passengers because the seat becomes hard and less absorptive [5]. At preload 200N, all seats were having similar stiffness across frequency of vibration. However, at preload 600N, Seat C produced greater stiffness than other seats. It may be expected that the comfort level of Seat C is worse than the other seats as heavier individual is seated on the Seat C compared to other seats. This observation is highly likely that the Seat C was fitted the foam with thinnest foam compared to other seats. This has been reported in some literatures that the stiffness increased when the thickness of foam decreased [7]–[10]. In addition, this observation may also be contributed by the shape of the seat itself which has more flat surface than other seats. Under compression load, both left and right side of the seat tended to move (being pulled) together while Seat A and B did not exhibit significant movement under compression.

Table 4. Mean value for stiffness of seat at different preload for frequencies from 2 to 20 Hz.

Seat	Seat A, N/m		+	Seat B, N/m		+	Seat C, N/m		+
Preload	Mean	SD		Mean	SD		Mean	SD	
200N	4.48e4	4.12e4		4.88e4	5.18e4		4.50e4	3.18e4	
400N	5.27e4	4.61e4	18	5.68e4	6.21e4	18	7.00e4	6.68e4	55
600N	7.26e4	6.70e4	62	7.62e4	5.29e4	55	1.13e5	1.04e4	151

Table 5. Mean value for damping at different preload

Seat	Seat A, N.s/m (mean)		+	Seat B, N.s/m (mean)		+	Seat C, N.s/m		+
Preload	Mean	SD		Mean	SD		Mean	SD	
200N	325.58	58		294.40	68		261.39	62	
400N	437.66	74	30	350.89	77	17	414.92	88	60
600N	649.60	102	90	472.29	103	59	647.07	178	155

Damping of the seat foam also increased when the preload increased as shown in Figure 5 and Table 4. The trend applied to all seats used in this test.

3.4 Limitations of the study

This study only observed the effect of the preload and vibration magnitudes on seat dynamic stiffness. Several aspects were not considered in this study such as the influence of the seat cover on the dynamic stiffness of the foam, and the design and shape of the seat foam. These factors can play significant roles in affecting the seat dynamic stiffness and these factors need to be considered for full study of seat dynamic stiffness.

4. Conclusions

For the effects of vibration magnitude, seat stiffness was found to be not affected significantly for frequency up to 20Hz. However, the damping changed significantly especially for frequency less than 5Hz. The seats dynamic characteristic has large effect of preload in terms of both stiffness and damping. Therefore, under real situation, occupant with higher weight will experience different comfort when seating on similar seat than occupant with smaller weight.

5. Acknowledgement

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6. References

- [1] W. N. Patten, S. Sha, and C. Mo, "A vibration model of open celled polyurethane foam automotive seat cushions," *J. Sound Vib.*, vol. 217, no. 1, pp. 145–161, 1998, doi: 10.1006/jsvi.1998.1760.

- [2] G. R. Blair, R. So, A. Milivojevic, and J. D. van Heumen, "Automotive Seating Comfort: Investigating the Polyurethane Foam Contribution-Phase 1," in SAE Technical Paper Series, Feb. 1998, vol. 1, no. 724, doi: 10.4271/980656.
- [3] C.-K. Chae, K.-J. Kim, H.-K. Jang, and Y.-H. Cho, "Characterization of Dynamic Properties of Polyurethane Foams for Automotive Seats By Vibration Tests," in The 29th International Congress and Exhibition on Noise Control Engineering, 2000, no. August, pp. 1–4.
- [4] J. A. Elliott et al., "In-situ deformation of an open-cell flexible polyurethane foam characterised by 3D computed microtomography," *J. Mater. Sci.*, vol. 37, no. 8, pp. 1547–1555, 2002, doi: 10.1023/A:1014920902712.
- [5] K. Ebe and M. J. Griffin, "Factors affecting static seat cushion comfort," *Ergonomics*, vol. 44, no. 10, pp. 901–921, 2001, doi: 10.1080/00140130110064685.
- [6] M. J. Griffin, *Handbook of human vibration*. Academic Press, 1990.
- [7] M. A. Koshute, "Influence of PU Foam Thickness, Density, and Hardness on Seat Cushion Durability," 2018.
- [8] M. Kolich, S. D. Essenmacher, and J. T. McEvoy, "Automotive seating: The effect of foam physical properties on occupied vertical vibration transmissibility," *J. Sound Vib.*, vol. 281, no. 1–2, pp. 409–416, Mar. 2005, doi: 10.1016/j.jsv.2004.03.058.
- [9] X. Zhang, Q. Zhang, Y. Li, C. Liu, and Y. Qiu, "Effect of the thickness of polyurethane foams at the seat pan and the backrest on fore-and-aft in-line and vertical cross-axis seat transmissibility when sitting with various contact conditions of backrest during fore-and-aft vibration," *Appl. Ergon.*, vol. 93, no. January, p. 103354, 2021, doi: 10.1016/j.apergo.2021.103354.
- [10] X. Zhang, Y. Qiu, and M. J. Griffin, "Transmission of vertical vibration through a seat: Effect of thickness of foam cushions at the seat pan and the backrest," *Int. J. Ind. Ergon.*, vol. 48, pp. 36–45, 2015, doi: 10.1016/j.ergon.2015.03.006.
- [11] T. E. Fairley and M. J. Griffin, "The apparent mass of the seated human body: Vertical vibration," *J. Biomech.*, vol. 22, no. 2, pp. 81–94, 1989, doi: 10.1016/0021-9290(89)90031-6.
- [12] N. A. A. Jalil and M. J. Griffin, "Fore-and-aft transmissibility of backrests: Effect of backrest inclination, seat-pan inclination, and measurement location," *J. Sound Vib.*, vol. 299, no. 1–2, pp. 99–108, 2007, doi: 10.1016/j.jsv.2006.06.053.
- [13] G. S. Paddan and M. J. Griffin, "Effect of seating on exposures to whole-body vibration in vehicles," *J. Sound Vib.*, vol. 253, no. 1, pp. 215–241, 2002, doi: 10.1006/jsvi.2001.4257.
- [14] Y. Qiu and M. J. Griffin, "Transmission of vibration to the backrest of a car seat evaluated with multi-input models," *J. Sound Vib.*, vol. 274, no. 1–2, pp. 297–321, 2004, doi: 10.1016/j.jsv.2003.05.015.
- [15] N. A. Abdul Jalil and M. J. Griffin, "Fore-and-aft transmissibility of backrests: Variation with height above the seat surface and non-linearity," *J. Sound Vib.*, vol. 299, no. 1–2, pp. 109–122, 2007, doi: 10.1016/j.jsv.2006.06.057.
- [16] G. Jianghua, H. Zhichao, H. Le, and X. Qunsheng, "Vertical vibration characteristics of seated human bodies and a biodynamic model with two degrees of freedom," *Sci. China Technol. Sci.*, vol. 54, no. 10, pp. 2776–2784, 2011, doi: 10.1007/s11431-011-4461-6.
- [17] L. Wei and J. Griffin, "The Prediction of Seat Transmissibility From Measures of Seat Impedance," *J. Sound Vib.*, vol. 214, no. 1, pp. 121–137, 1998, doi: 10.1006/jsvi.1998.1540.
- [18] S. Tufano and M. J. Griffin, "Nonlinearity in the vertical transmissibility of seating: The role of the human body apparent mass and seat dynamic stiffness," *Veh. Syst. Dyn.*, vol. 51, no. 1, pp. 122–138, 2013, doi: 10.1080/00423114.2012.715652.
- [19] T. E. Fairley and M. J. Griffin, "A Test Method for the Prediction of Seat Transmissibility," *SAE Tech. Pap. Ser.*, vol. 1, 2010, doi: 10.4271/860046.
- [20] E. M. Whitham and M. J. Griffin, "Measuring Vibration on Soft Seats," *SAE Tech. Pap. Ser.*, vol. 1, 2010, doi: 10.4271/770253.
- [21] C. Corbridge, M. J. Griffin, and P. R. Harborough, "Seat dynamics and passenger comfort," *Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit*, vol. 203, no. 1, pp. 57–64, 1989, doi: 10.1243/PIME_PROC_1989_203_209_02.