Pertanika J. Sci. & Technol. 31 (3): 1267 - 1278 (2023)

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

The Effect of Preload, Density and Thickness on Seat Dynamic Stiffness

Azmi Mohammad Hassan[1], Khairil Anas Md Rezali[1]*, Nawal Aswan Abdul Jalil[1], Azizan As'arry[1] and Mohd Amzar Azizan[2,3]

[1]Sound and Vibration Research Group (SVRG), Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia (UPM), 43400 UPM Serdang, Selangor, Malaysia
[2]Higher Colleges of Technology (HCT), Abu Dhabi 25026, United Arab Emirates
[3]Khalifa bin Zayed Air College (KBZAC), Abu Dhabi, United Arab Emirates

ABSTRACT

The vibration transferred to the car floor transmits to the human body through the seat structure, and the typical design of the seat structure consists of several components such as seat frame and seat cushion. The material widely used as seat cushion is open-cell polyurethane (PUR) foam; when under vibration, it will behave dynamically. Factors such as mechanical properties and material thickness of PUR can affect its behaviour and performance and the amount of vibration transmits to the human body. This work measures the PUR dynamic stiffness for different material densities and thicknesses. The test was conducted using an indenter head with a flat surface since it was a less expensive method, and quicker measurement could be done. The force sensor was placed within the indenter structure to measure the load transmitted to the seat and acceleration data acquired by the accelerometer, which was mounted on a shaker test plate. Foam materials with 30 kg/m^3 and 44 kg/m^3 with 30 mm and 50mm thickness are used in the experiment with the amount of preload applied of 20 N,30 N and 40 N. Seat stiffness increased when the preload increased from 20 N to 40 N, and a similar trend occurred when foam thickness decreased. The lower density of PUR resulted in a greater increase of seat stiffness and damping across the frequency 0-30 Hz compared to a higher density of PUR. This study concluded that thickness, preload, and density significantly affect seat dynamic stiffness.

Keywords: Dynamic stiffness, seat cushion, seat dynamic, seat vibration

ARTICLE INFO

Article history:
Received: 25 February 2022
Accepted: 16 August 2022
Published: 31 March 2023

DOI: https://doi.org/10.47836/pjst.31.3.08

E-mail addresses:
azmi@outlook.my (Azmi Mohammad Hassan)
khairilanas@upm.edu.my (Khairil Anas Md Rezali)
nawalaswan@upm.edu.my (Nawal Aswan Abdul Jalil)
zizan@upm.edu.my (Azizan As'arry)
mazizan@hct.ac.ae (Mohd Amzar Azizan)
* Corresponding author

ISSN: 0128-7680
e-ISSN: 2231-8526

INTRODUCTION

The seat is a critical structure of a vehicle because vibration transmitted through the seat can affect both human health and driving comfort (Griffin, 1990). Many methods have been developed numerically and experimentally to assess seat performance in attenuating or influencing vibration; however, the findings have not always been consistent due to the nonlinearity of the material used for the seat and the human responses (Karen et al., 2012). The seat vibrations due to the movement of a car are transmitted to the car floor, which is later transmitted to the human body through seat structure and can be complex, involving many factors. The seat can be considered a structure that can influence comfort significantly compared to other factors such as air conditioning and noise level (Kamp, 2012). It is because the human body has the most direct contact with the vehicle seat (Bang et al., 2017).

Typical seat components include several components, such as a seat frame and seat cushion. Open-cell polyurethane (PUR) foam has been widely used in the automotive industry as a cushion for seat structure (Patten et al., 1998). Open cell PUR provides advantages such as excellent compression properties, ease of hardness adjustment, superior resilience, and ability to mould shapes, and it is cheap, too (Murata et al., 2014; Patten et al., 1998). The material structure comprises a cellular matrix filled with air free from loads. When subjected to impact, the air trapped in the cell will squeeze through the cell structure. Hence the cell size of the cellular matrix will affect its mechanical properties and behaviour under compression.

The static and dynamic properties of PUR used as a seat cushion can affect the comfort level experienced by the human body (Choi & Kim, 2020). Hence modification of material structure, such as increasing crosslinking density of the polymer matrix, can improve the comfort level (Wada et al., 2008). Instead of modifying the structure of the material, the use of an optimal thickness relative to its mechanical property can also improve the level of comfort (Deng et al., 2003; Patten et al., 1998; Zhang & Dupuis, 2011). Dynamic stiffness of the foam becomes one of the important parameters in determining the seat performance (Kreter, 1985) and by measuring dynamic stiffness, the behaviour of the foam under load can be investigated.

Dynamic stiffness property can be evaluated using the indentation test method by applying preloads using an indenter pad with an SIT-BAR shape (Wei & Griffin, 1998; Tufano & Griffin, 2013; Whitham & Griffin, 2010; Zhang et al., 2015). The load imposed on the PUR material significantly affects material stiffness; when the load increases, the stiffness and damping increase (Wei & Griffin, 1998). Other findings showed that foam thickness less affected damping, but it depends more on the frequency (Zhang et al., 2015).

The seat dynamic stiffness is an important characteristic of predicting seat transmissibility. As mentioned previously, the dynamic stiffness of seat material can be affected by various factors. Three main factors are usually assessed when selecting seat material with respect to its dynamic stiffness: the effects of seat thickness, the preload force and seat densities apart from the seat design. However, it is still unclear how significantly seat dynamic stiffness is affected by the mentioned factors. In addition, all previous studies did not investigate the effects of contact area, contact force, and material density in a single study. The seat foam usually behaves non-linearly, so a study of this will help us further understand how all variables influence the material dynamic stiffness. This work aimed to investigate the dynamic stiffness characteristics of automotive seats, emphasising the effects of thickness, preload, and material densities. The increase in thickness was expected to reduce seat dynamic stiffness. Seat foam density can be between 30 kg/m^3 to 50 kg/m^3 in accordance with Euromoulder Association (http://euromoulders.org). It was also expected that the dynamic stiffness of the seat would increase as the density of the material decreased. The findings in this work can provide the researchers and seat designers with an insight into how density and thickness will affect vibration transmission. Even though few previous publications are studying the effect of the thickness of seat foam on dynamic stiffness, it was not discussed thoroughly, and so far, the effect of foam density was not properly studied.

METHODS

Test Apparatus and Setup

The study employed a test rig for the measurement of dynamic stiffness testing, including the structural test frame, force sensor, vibration shaker, and accelerometer (Figure 1). The force sensor used in the experiment was Futek LTH-350, a doughnut-type sensor which

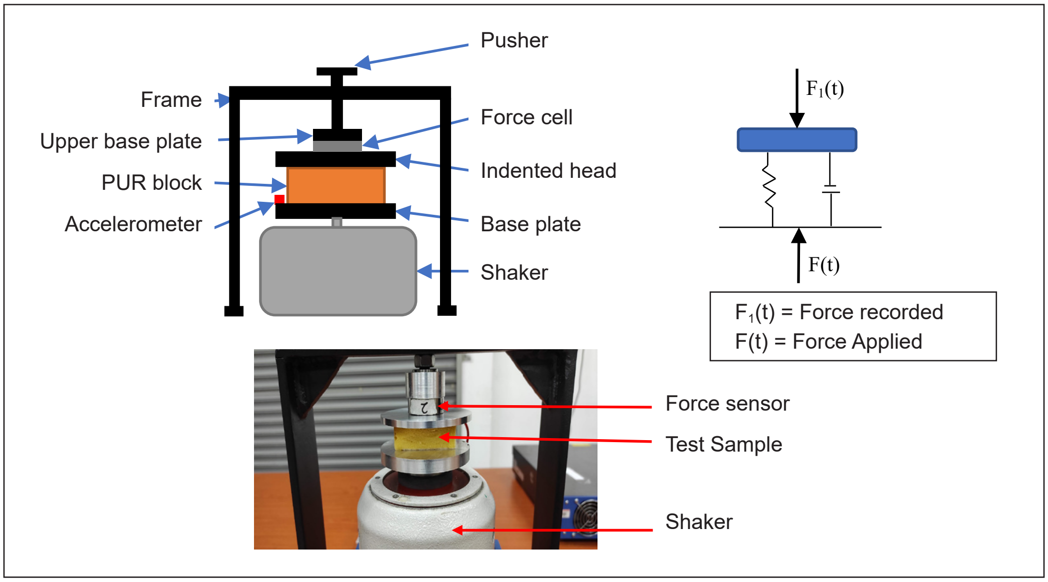

Figure 1. Schematic and actual view of the test setup

has a maximum loading capacity of 500lb (~227kg). The acceleration in the vertical direction was measured using a triaxial IEPE Dytran 3023A accelerometer with a sensitivity of 10.78 mV/g in the respective axis. The vibration was generated using Tira Vibration Test System, and vibration input was configured using the LMS SCADA Mobile system. LABVIEW software provided real-time load control monitored the power spectral density and acquired fresh measurement data for both the force sensor and accelerometer. The coherence of system input and output was monitored during experimental works, and the coherence within the frequency of interest is shown in Figure 2. Coherence close to 1 indicated that the output signal was linearly correlated with the input signal (Zhang et al., 2015).

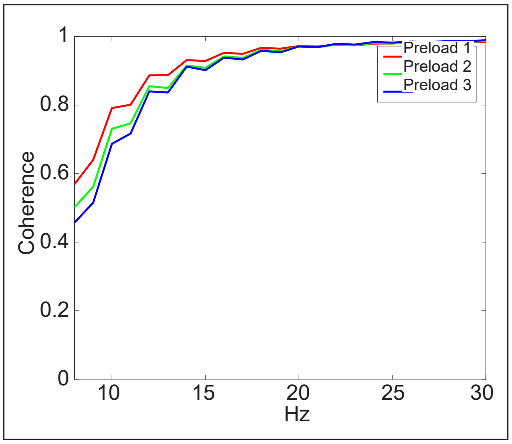

Figure 2. System input-output coherence

Test Sample and Procedures

The test sample was an open cell polyurethane foam (PUR) with a density of 44 kg/m^3 and 30 kg/m^3 with a sample's dimension of 60 mm × 60 mm and thickness of 30 mm, 40 mm and 50 mm as shown in Table 1. All samples in this study agreed with Euromoulders Association's suggestion for actual seat applications (http://euromoulder.org). Samples 1 and 2 were used to investigate the effects of foam density and preload, whilst Samples 2, 3 and 4 were employed to study the effects of material thickness on seat dynamic stiffness. Three different preloads were applied in this study which was 30 N, 40 N and 50 N. The test frequency the shaker (TIRAvib with a maximum force of 200 N) generated was between 1 and 100Hz and 8 ms^{-2} r.m.s. acceleration (unweighted) or 1.5 r.m.s acceleration (weighted W_k according to ISO-2361-1) with a spectral density, as shown in Figure 3. The input spectra were high, between 10 to 30Hz and similar across different settings. The study measured the vibration and force signals of the material at the lower and upper surfaces of the foam (Figure 1). The data recorded were sampled at 2048 samples per second and

Table 1
Test sample characteristics

Parameter	***Sample 1***	***Sample 2***	***Sample 3***	***Sample 4***
Size	60 mm × 60 mm	60 mm × 60 mm	60 mm × 60 mm	60 mm × 60 mm
Thickness	50 mm	50mm	40 mm	30mm
Density	30 kg/m^3	44 kg/m^3	44 kg/m^3	44 kg/m^3
Origin	Foam Block	Car Seat	Car Seat	Car Seat

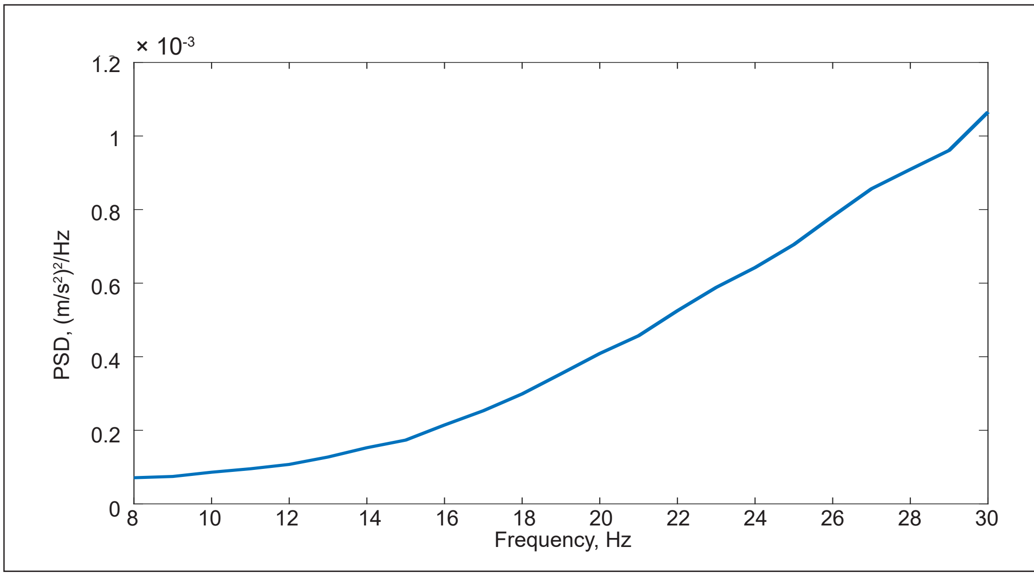

Figure 3. Median power spectral density for input acceleration weighted W_k according to ISO2631-1 in logarithmic scale

filtered by Butterworth low pass filter with 2 poles and a cut-off frequency of 50 Hz the analysis of the data was done using MATLAB.

Sample Scale

This experiment was conducted using a small-scale shaker and sample size. The maximum load applied to the small shaker was about 200 N. Because the samples used in this study were much smaller than the actual seat size studied previously (Wei & Griffin, 1998), the loads applied to the materials differed. The loads applied in this study were chosen based on similar force per unit area to make it comparable to the actual size and load on the actual seat, as conducted in previous studies. The PUR sample sizing was estimated based on the approximated actual seat size and load applied by (Wei & Griffin, 1998).

As shown in Table 2, the force per unit area for small-scale foam samples used in this work was identical to the force per unit area for the actual seat foam size used (Wei & Griffin, 1998). It can be concluded that the amount of preload for small-scale samples of 30 N, 40 N, and 50 N was identical to full-scale samples of 400 N, 500 N and 600 N, accordingly. Force per unit area, P, is calculated using Equation 1.

$$P = \frac{F}{A} \tag{1}$$

Where F is the applied force and A is the area impacted by the applied force.

Table 2
Force per unit area

Area, mm^2	Force, N	Force per unit area, MPa	Source
3600	30	0.0083	
3600	40	0.011	This work
3600	50	0.014	
47047	400	0.0085	
47047	500	0.011	(Wei & Griffin, 1998)
47047	600	0.013	

Theory of Dynamic Stiffness

Dynamic stiffness of the seat, *S(f),* was given by Griffin (1990) in Equation 2:

$$S(f) = \frac{F_{io}(f)}{(-(2\pi f)^{-2})\ A_{ii}(f)} \qquad (2)$$

Where $F_{io}(f)$ is the cross-spectral density of the input acceleration and the output force transmitted by the material, $A_{ii}(f)$ is the power spectral density of the input acceleration, and f is the frequency in Hz.

The dynamic stiffness was assumed to be represented by the Kelvin Voigt model (Equation 3).

$$S(f) = K(f) + 2\pi f C(f) * i \qquad (3)$$

Where K is the stiffness of the material and C is the material viscous damping coefficient.

The complex number, $S(f)$, is called dynamic stiffness and was used in preference to the mechanical impedance (the ratio of force over velocity) because dynamic stiffness provided an easier approach to identifying the equivalent stiffness, *K* and the equivalent damping, *C*. Both seats/foam parameters of *K* and *C* can be obtained using the curve fitting method from real and imaginary components of dynamic stiffness, $S(f)$ (Wei & Griffin, 1998; Tufano & Griffin, 2013; Zhang et al., 2015) but are not conducted in this study.

RESULTS

Effect of Preload on the PUR Dynamic Stiffness

Figure 4 displays the dynamic stiffness for density 44kg/m^3 at the variation of preloads at 20N, 30N and 40N. From the plot, stiffness increases with increasing preload force from 20 N to 40 N. A similar trend was also observed for PUR foam with lower density (30 kg/m^3). Increasing the preload will increase the dynamic stiffness of the foam.

At all preloads, foam stiffness increased as the vibration frequency increased for frequencies between 8 to 15 Hz. The damping of PUR foam was also found to increase with the increased preload amount, although they were not significant for each preload.

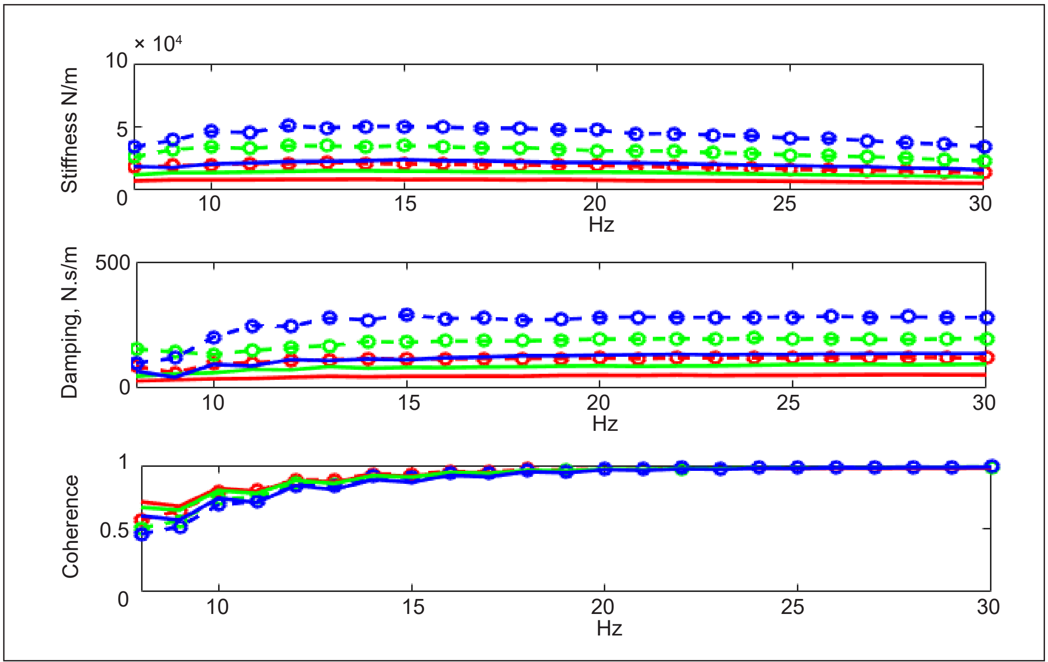

Figure 4. Dynamic stiffness for PUR with 30 kg/m^3(-o-) and 44 kg/m^3 (-) at preload of 20 N (----), 30 N (----) and 40 N (----)

Effect of Material Density on PUR Dynamic Stiffness

Figure 5 presents the effects of foam density on the modulus of dynamic stiffness. PUR foam with a density of 30 kg/m^3 produced greater stiffness than PUR foam with 44 kg/m^3. Also, the damping of lower-density PUR foam was greater than PUR foam with higher density.

Open-celled PU foam material structure consists of PU material and air-filled cells. The entrapped air movement is unrestricted. Under applied preload, the PU foam with lower density loses more air (due to greater compression) than the PU foam with higher density. Greater reduction of air in the cells makes the PU foam stiffer and less flexible. The result is consistent with findings by (Tufano & Griffin, 2013).

Figure 6 exhibits the minimum and maximum stiffness for PUR foam with a density of 30 kg/m^3 and 44 kg/m^3. The differences in maximum stiffness at 20 N, 30 N and 40 N vary by 61%, 56% and 52%, respectively, for both densities.

Effect of Material Thickness on PUR Dynamic Stiffness

Figure 7 shows that foam stiffness increased when the thickness decreased. The result was in line with Zhang et al. (2015). For both thicknesses, at all preloads, the stiffness had slightly increased up to 15 Hz, and beyond 15 Hz, it produced a slight decrease to 30 Hz. The damping had a slightly increased trend up to 30 Hz at all preloads for both thicknesses, and the damping increased when the thickness increased.

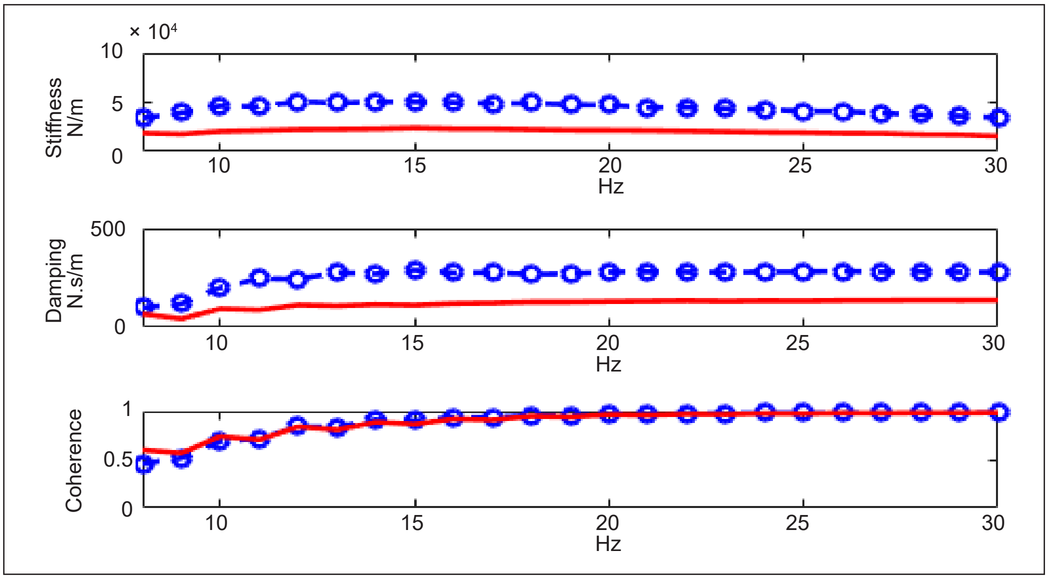

Figure 5. Dynamic stiffness for PUR with 30 kg/m³ (-o-) and 44 kg/m³ (-) at 40 N

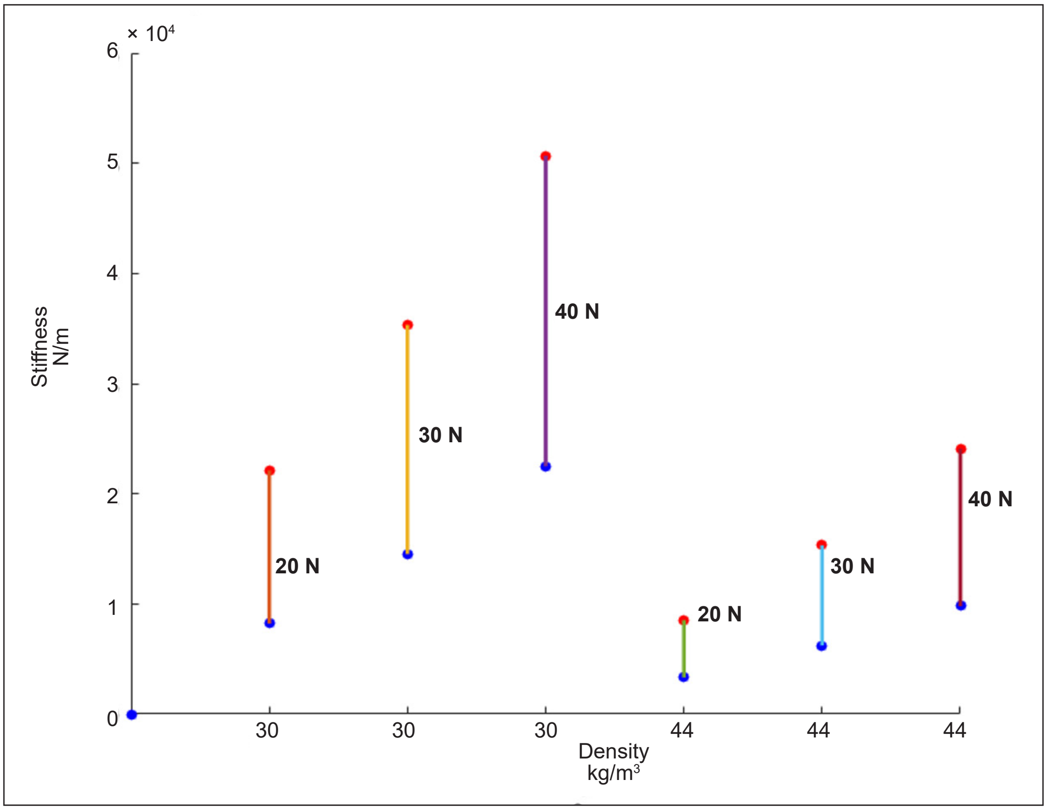

Figure 6. Maximum and minimum stiffness for PUR foam samples at preload of 20 N, 30 N and 40 N in the frequency range of 0-30 Hz

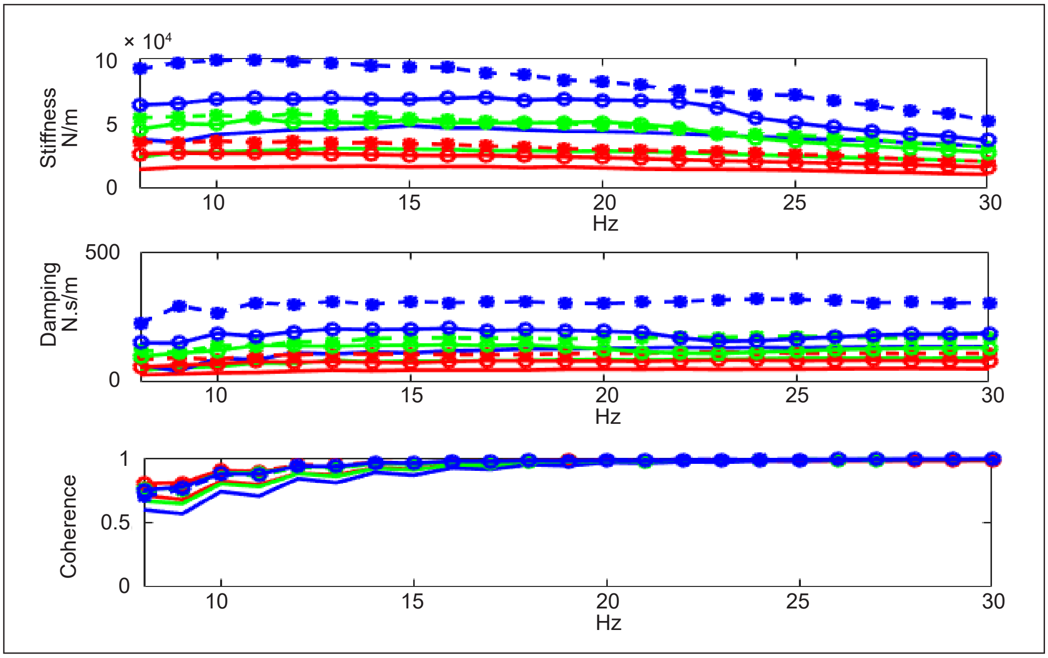

Figure 7. Dynamic stiffness of PUR foam with density 44 kg/m^3 a thickness of 50 mm (-), 40 mm (-o-) and 30 mm (-*-) at preload of 20 N (----), 30 N (----) and 40 N (----)

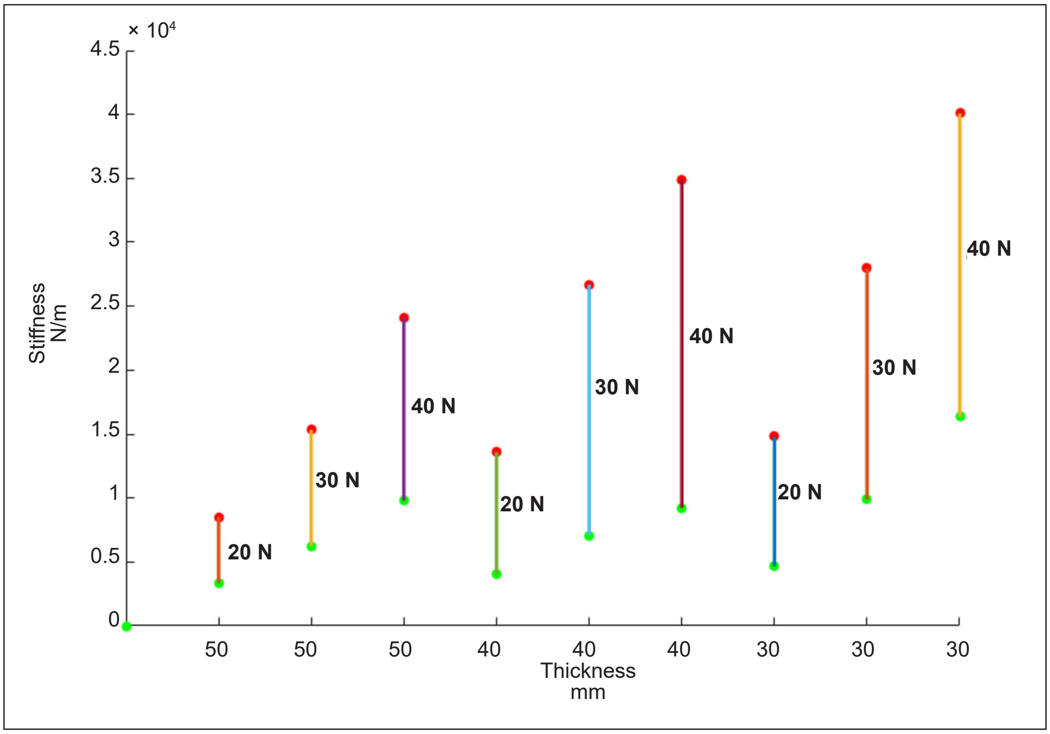

Figure 8. Maximum and minimum foam stiffness for PUR with density 44 kg/m^3 at 50 mm and 30 mm

As shown in Figure 8, a higher maximum stiffness was observed for the lower thickness of PUR foam, while at each thickness, the maximum stiffness increased when the preload increased. At 40 N, the PUR sample with a thickness of 50 mm produced the lowest maximum stiffness of 2.4×10^4 N/m and the higher maximum stiffness increased by 40% and 46% when using a PUR sample with a thickness of 40 mm and 30 mm. Similarly, the maximum stiffness at 50mm thickness is $1.53 \text{ x} 10^4$ N/m and 0.8×10^4 N/m which increased by 37% and 42% at preload of 30 N and 43% and 45% at 20 N, accordingly.

DISCUSSION

Effect of Preloads on the Material Stiffness and Damping

The stiffnesses of PUR foams were found to be affected when the applied force on the PUR foam varied. The results align with previous studies' findings (Wei & Griffin, 1998; Tufano & Griffin, 2013; Zhang et al., 2015). A similar finding was also obtained by Zhang et al. (2015) when evaluating static stiffness, where a higher thickness of seat foam will decrease its stiffness. As reported by Ebe & Griffin (2001), higher stiffness of seat foam will reduce seat comfort; however, this still depends on the damping coefficient because the damping coefficient can affect the system's settling time.

Effect of Material Thickness on the Material Stiffness and Damping

PUR foam behaviour under vibration might be influenced by the damping and entrapped air in the cells. As shown in the results, at 40 N, the preload applied on PUR foam density of 30 kg/m^3 will require more displacement than PUR foam with a density of 44 kg/m^3. Under greater displacement, the cell's structure becomes denser, and more resistance from the entrapped air will require a higher load. This behaviour indicated that the foam material might be in the densification stage when subjected to preload of 40N (Qiu et al., 2019). Similar behaviour was also observed when changing the thickness from 50 mm to 30 mm, as the thinner foam will generate more entrapped air resistance under a similar preload compared to thicker foam. As shown in Figure 5, even though the damping decreased when the thickness increased, there is only a slightly different between both thicknesses. Therefore, the thickness of foam has a less significant impact on the damping of PUR foam, while Zhang et al. (2015) reported that damping has more impact due to frequency variation.

Limitations of the Study

Although the results are in line with all previous work, the study was conducted on samples significantly smaller than the one installed in a vehicle seat. The smaller size of foam is expected to produce lower air-trapped responses compared to a larger sample. In addition, a greater density of the foam should also be employed. Vehicle manufacturers may use greater density than the one studied here in the range of 40 kg/m^3 to 60 kg/m^3.

Also, both materials were selected based on their type (open-celled polyurethane foam) and density. Other factors such as composition, number of cells and chemical properties were unknown, which can be a factor in the difference they had in this study.

CONCLUSION

This study found that over the frequency of 10–30 Hz, the lower density of PUR foam will produce greater stiffness. Similar behaviour was observed when using thinner foam and when subjected to greater preload. From the findings, it can be concluded that using different densities of foam and thickness will affect the comfort of sitting on the seat. It is important for engineers to properly select seat foam and verify its performance because the dynamic stiffness, based on this study, is significantly influenced by its thickness, density, and preload.

ACKNOWLEDGEMENT

The authors would like to appreciate and acknowledge the financial support provided by the Universiti Putra Malaysia (UPM) via Geran Putra (GP-IPS) (Vot. number: 9689600).

REFERENCES

Bang, J. H., Lee, C. A., Kim, H. Y., Kim, H. J., & Choi, K. Y. (2017). Optimization of the static properties of seat foam to improve the seating comfort. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, *231*(14), 1945-1960. https://doi.org/10.1177/0954407016688782

Choi, H. J., & Kim, J. H. (2020). Static and dynamic comfort properties of polyurethane foams including a flexible amine crosslinker. *Journal of Industrial and Engineering Chemistry*, *90*, 260-265. https://doi.org/10.1016/j.jiec.2020.07.021

Deng, R., Davies, P., & Bajaj, A. K. (2003). Flexible polyurethane foam modelling and identification of viscoelastic parameters for automotive seating applications. *Journal of Sound and Vibration*, *262*(3), 391-417. https://doi.org/10.1016/S0022-460X(03)00104-4

Ebe, K., & Griffin, M. J. (2001). Factors affecting static seat cushion comfort. *Ergonomics*, *44*(10), 901-921. https://doi.org/10.1080/00140130110064685

Griffin, M. J. (1990). *Handbook of Human Vibration*. Academic Press.

Kamp, I. (2012). The influence of car-seat design on its character experience. *Applied Ergonomics*, *43*(2), 329-335. https://doi.org/10.1016/j.apergo.2011.06.008

Karen, I., Kaya, N., Öztürk, F., Korkmaz, I., Yildizhan, M., & Yurttaç, A. (2012). A design tool to evaluate the vehicle ride comfort characteristics: Modeling, physical testing, and analysis. *International Journal of Advanced Manufacturing Technology*, *60*, 755-763. https://doi.org/10.1007/s00170-011-3592-z

Kreter, P. E. (1985). Polyurethane foam physical properties as a function of foam density. *Journal of Cellular Plastics, 21*(5), 306-310. https://doi.org/10.1177/0021955X8502100502

Murata, S., Ito, H., & Sopher, S. (2014). Polyurethane-free lightweight automotive seat. *SAE International Journal of Materials and Manufacturing*, *7*(3), 655-661. https://doi.org/10.4271/2014-01-1033

Patten, W. N., Sha, S., & Mo, C. (1998). A vibrational model of open celled polyurethane foam automotive seat cushions. *Journal of Sound and Vibration*, *217*(1), 145-161. https://doi.org/10.1006/jsvi.1998.1760

Qiu, D., He, Y., & Yu, Z. (2019). Investigation on compression mechanical properties of rigid polyurethane foam treated under random vibration condition: An experimental and numerical simulation study. *Materials*, *12*(20), Article 3385. https://doi.org/10.3390/ma12203385

Tufano, S., & Griffin, M. J. (2013). Nonlinearity in the vertical transmissibility of seating: The role of the human body apparent mass and seat dynamic stiffness. *Vehicle System Dynamics*, *51*(1), 122-138. https://doi.org/10.1080/00423114.2012.715652

Wada, H., Toyota, Y., Horie, A., Sasaki, T., Suzuki, C., & Fukuda, H. (2008). Automotive seating foams with excellent riding comfort prepared by a novel polypropylene glycol. *Polymer Journal*, *40*(9), 842-845. https://doi.org/10.1295/polymj.pj2008098

Wei, L., & Griffin, J. (1998). The prediction of seat transmissibility from measures of seat impedance. *Journal of Sound and Vibration*, *214*(1), 121-137. https://doi.org/10.1006/jsvi.1998.1540

Whitham, E. M., & Griffin, M. J. (2010). Measuring vibration on soft seats. In *1977 International Automotive Engineering Congress and Exposition* (pp. 1-12). SAE International in United States. https://doi.org/10.4271/770253

Zhang, L., & Dupuis, R. (2011). Measurement and identification of dynamic properties of flexible polyurethane foam. *Journal of Vibration and Control*, *17*(4), 517-526. https://doi.org/10.1177/1077546310363777

Zhang, X., Qiu, Y., & Griffin, M. J. (2015). Transmission of vertical vibration through a seat: Effect of thickness of foam cushions at the seat pan and the backrest. *International Journal of Industrial Ergonomics*, *48*, 36-45. https://doi.org/10.1016/j.ergon.2015.03.006