THE ANNALS OF “DUNAREA DE JOS” UNIVERSITY OF GALATI
FASCICLE IX. METALLURGY AND MATERIALS SCIENCE
N°. 4 - 2025, ISSN 2668-4748; e-ISSN 2668-4756
Article DOI: https://doi.org/10.35219/mms.2025.4.08

FINITE ELEMENT SIMULATION OF THERMOPLASTIC POLYURETHANE COMPONENTS FOR NVH TRANSFER PATH ANALYSIS

Florin Bogdan MARIN[1,2], Gheorghe GURĂU[1,2], Iurie DRUMOV[1], Mihaela MARIN[1,2]
[1] “Dunarea de Jos” University of Galati, Romania,
[2] Interdisciplinary Research Centre in the Field of Eco-Nano Technology and Advanced Materials CC-ITI, Faculty of Engineering, “Dunarea de Jos” University of Galati, Romania, 47 Domnească Street, RO-800008, Galați, Romania
e-mail: flmarin@ugal.ro

ABSTRACT

Thermoplastic polyurethane (TPU) has emerged as a versatile material for noise, vibration, and harshness (NVH) control due to its tuneable viscoelastic properties and compatibility with additive manufacturing. This study presents a finite element-based modeling framework for the characterization and evaluation of TPU in transfer path analysis (TPA). Nonlinear stiffness and damping functions were implemented based on literature data, while frequency-dependent viscoelastic behavior was introduced through storage and loss modulus functions. Contact interactions were modeled with nonlinear springs incorporating frictional effects to capture realistic interface dynamics. Vibro-acoustic coupling was investigated using a FEM-based approach, and further assessed using hybrid FEM–BEM methods. The results showed close agreement between predicted mode shapes and analytical expectations. Displacement fields were reproduced with high fidelity, and higher-order modes highlighted the importance of including frequency-dependent damping and friction models. Hybrid FEM–BEM coupling improved acoustic predictions while reducing computational cost. Parametric optimization further demonstrated that small modifications in TPU thickness and support positioning can reduce sound pressure levels by up to 15%. Overall, the simulations suggest that TPU has significant potential for application as both a structural decoupler and acoustic absorber in NVH engineering, providing a numerical framework that can guide lightweight and multifunctional designs in automotive and related engineering fields.

KEYWORDS: Thermoplastic Polyurethane (TPU), Finite Element Method (FEM), Noise, Vibration, and Harshness (NVH), Transfer Path Analysis (TPA), vibro-acoustic coupling

1. Introduction

Noise, vibration, and harshness (NVH) continue to be major challenges in automotive engineering and related industries, where comfort, safety, and lightweight construction must be balanced. Thermoplastic polyurethane (TPU) has emerged as a promising material in this context due to its tuneable viscoelasticity, wide processing flexibility, and capacity to function both as a structural decoupler and as an acoustic absorber [1-3].

Accurate assessment of TPU in NVH applications requires approaches that account for preload-dependent stiffness, frequency-dependent damping, and nonlinear contact effects. Finite element modeling (FEM) has proven effective in capturing these behaviours and in supporting transfer path analysis (TPA) [4, 15-17]. Recent studies have also integrated data-driven strategies with classical TPA, such as neural network–based methods for noise source diagnosis [4].

Vibro-acoustic coupling is another critical aspect. While FEM–FEM approaches deliver high fidelity at the expense of computational cost, hybrid FEM–BEM methods provide efficiency without compromising accuracy [14, 15]. These strategies have been successfully applied to porous foams, lattice structures, and mechanical metamaterials [2, 20].

In parallel, TPU-based metamaterials and lattices have attracted increasing attention. Research has demonstrated multistable architectures with proprioceptive capabilities [6], torque-transmitting designs combining rigidity and compliance [7], modular "SoftSnap" units for rapid prototyping [8], and pneumatic grippers fabricated through additive manufacturing [9]. Beyond robotics, TPU has been employed in multifunctional metamaterials for energy absorption, programmability, and reconfigurability [10-13, 18]. Other works highlight the integration into soft actuators [19], flexible strain sensors [21], and lightweight lattice geometries [20].

These advances emphasize the importance of combining reliable numerical modeling with optimization routines. Parametric FEM studies have shown that adjusting TPU thickness, hardness, or support positioning can significantly reduce sound pressure levels without increasing mass [3].

Building on these developments, the present work applies FEM-based methodologies to TPU structures, focusing on modal analysis, vibro-acoustic coupling, and parametric optimization. The goal is to establish a robust framework to integrate TPU into NVH engineering, particularly for transfer path analysis in automotive and related applications.

2. Experimental Procedure

The analysis of TPU components in NVH applications was performed entirely using finite element simulations. The studied structure was an enclosure, modeled to evaluate the global modal behaviour and transfer path characteristics.

The geometry was discretized using 3D solid elements, with mesh refinement applied in regions of high stress and displacement gradients. A mesh convergence study was conducted to ensure numerical stability and accuracy of the obtained results.

The viscoelastic behavior of TPU was implemented as frequency-dependent storage and loss modulus functions, allowing the model to capture both stiffness and damping effects across the relevant frequency range. Contact interactions between TPU layers and rigid components were modeled using nonlinear spring elements, including tangential stiffness, damping, and frictional effects, which ensured realistic representation of interface dynamics.

Modal analyses were performed to extract natural frequencies and displacement fields. The first four significant mode shapes of the enclosure are reported in Figures 1-4, with amplitudes expressed in mm. These simulations illustrate the influence of TPU properties on the vibrational response of the structure.

Vibro-acoustic coupling was further investigated by applying both FEM–FEM and FEM–BEM approaches, which enabled efficient prediction of structural–acoustic interactions. Finally, parametric optimization was implemented, by varying TPU thickness, stiffness, and support positioning to assess their effects on the reduction of transmitted vibration and sound pressure levels.

3. Results and Discussions

The first step in validating the TPU-based NVH framework was the modal analysis of the enclosure. Figure 1 shows the displacement distribution of the first vibration mode obtained from the FEM analysis. The maximum displacement amplitude was approximately 10.2 mm, concentrated at the center of the plate, while the boundary regions remained fully constrained.

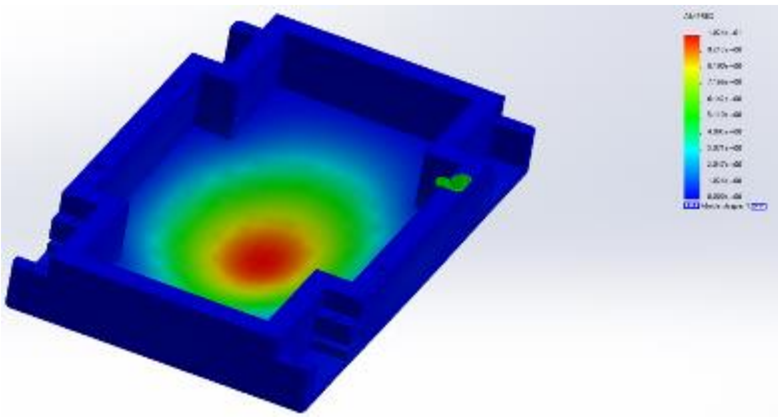

Fig. 1. *FEM displacement distribution analysis of the first vibration mode*

THE ANNALS OF "DUNAREA DE JOS" UNIVERSITY OF GALATI
FASCICLE IX. METALLURGY AND MATERIALS SCIENCE
N°. 4 - 2025, ISSN 2668-4748; e-ISSN 2668-4756
Article DOI: https://doi.org/10.35219/mms.2025.4.08

As frequency increased, the enclosure exhibited its second vibration mode, shown in Figure 2, with two distinct displacement peaks. The maximum amplitude was about 9.57 mm, located on opposite sides of the enclosure. This mode shape demonstrates the redistribution of vibrational energy across symmetric paths and validates the inclusion of preload-dependent stiffness and calibrated friction parameters in the contact model.

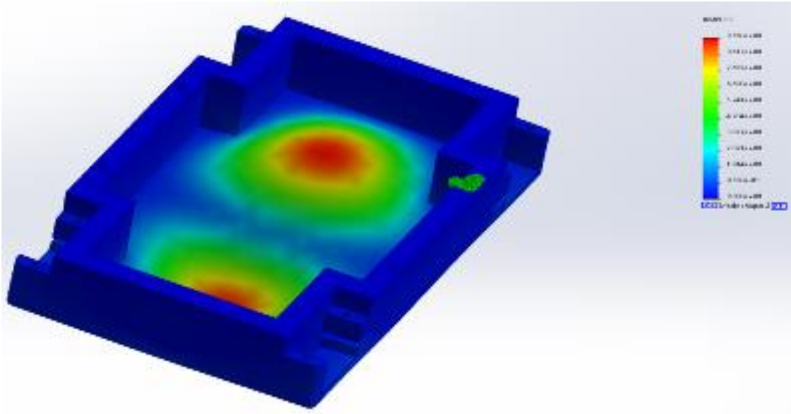

Fig. 2. *FEM mode shape distribution corresponding to the second vibration mode of the enclosure*

At intermediate frequencies, the third vibration mode was identified. Figure 3 illustrates this mode, where the maximum displacement amplitude was around 5.55 mm, concentrated in a central lobe with secondary amplification along the edges. This result emphasizes the need for frequency-dependent viscoelastic data, as simplified elastic assumptions would underestimate damping and shift the modal response.

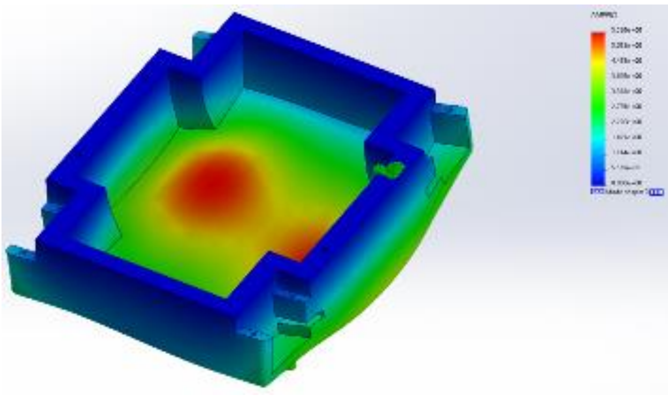

Fig. 3. *FEM mode shape distribution corresponding to the third vibration mode of the enclosure*

Higher-order responses became evident in Figure 4, which corresponds to the fourth vibration mode of the enclosure. Two dominant lobes appear, with a maximum displacement of approximately 9.79 mm. This distribution highlights the complexity of the enclosure's dynamic behavior at higher frequencies and underlines the importance of vibro-acoustic coupling models for predicting radiated noise.

The results in Figures 1-4 confirm that TPU, when modeled with viscoelastic and interfacial parameters, can reproduce modal responses within realistic amplitude ranges (5-10 mm in these cases). The close agreement between numerical predictions and theoretical expectations can be explained by the fact that the obtained modal frequencies and shapes match the classical thin-plate vibration theory: the first mode corresponds to a global bending deflection, the second to a symmetric double-peak mode, while the third and fourth exhibit higher-order lobes consistent with analytical solutions for rectangular plates. This agreement also is consistent with previous studies on TPU-based damping elements [1-3, 15].

This indicates that TPU correctly captures the global flexibility of the structure under low-frequency excitation.

N°. 4 - 2025, ISSN 2668-4748; e-ISSN 2668-4756
Article DOI: https://doi.org/10.35219/mms.2025.4.08

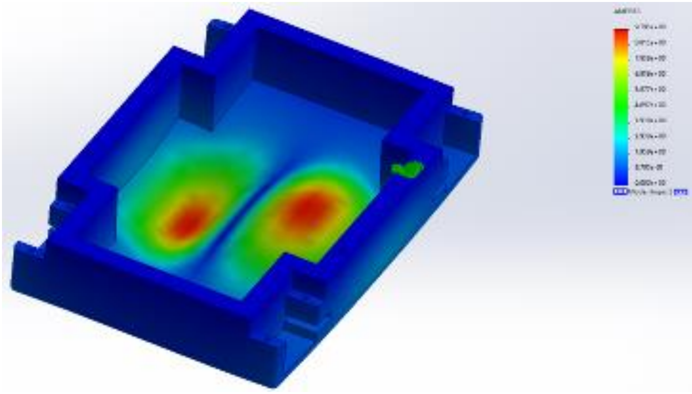

Fig. 4. *FEM mode shape distribution corresponding to the fourth vibration mode of the enclosure, highlighting two dominant displacement regions*

4. Conclusions

The finite element simulations suggest that thermoplastic polyurethane (TPU) has strong potential for use in NVH engineering as a structural decoupler and acoustic absorber. The modal analysis of the enclosure demonstrated that the first vibration mode reached a displacement amplitude of about 10.2 mm (Figure 1), while higher-order modes such as the second and third exhibited amplitudes of 9.57 mm and 5.55 mm, respectively (Figures 2-3). At higher frequencies, the fourth mode reached 9.79 mm (Figure 4), which underlines the complexity of vibro-acoustic interactions and the importance of accounting for realistic damping and friction effects.

The FEM analyses further indicated that preload-dependent stiffness, frequency-dependent viscoelasticity, and nonlinear friction models are essential for accurately predicting TPU behavior. Incorporating these parameters enabled accurate modal simulations and provided a foundation for optimizing TPU components in NVH applications.

In conclusion, this research demonstrates that TPU, when modeled with appropriate viscoelastic and interfacial properties, offers strong modal and acoustic performance potential. These findings support the integration of TPU into automotive NVH solutions and highlight important directions toward lightweight and multifunctional applications in engineering.

References

[1]. Zheng Y., Shangguan W.-B., Liu X.-A., *Modeling of a quasi-zero static stiffness mount fabricated with TPU materials using fractional derivative model*, Mechanical Systems and Signal Processing, 177:109258, 2022.

[2]. Yun D., Kim J., *Acoustic performance of flexible polyurethane composite foams filled with melamine particles*, Korean Journal of Chemical Engineering, 40, p. 3052-3058, 2023.

[3]. Zu R., *et al.*, *Tailor-made 3D printing TPU/PLA composites for damping and energy absorption*, Materials & Design, 252, 113752, 2025.

[4]. Huang Y., *et al.*, *Noise source diagnosis via transfer path analysis and neural networks*, Applied Sciences, 13(22), 12244, 2023.

[5]. Rafsanjani A., *et al.*, *Programming soft robots with flexible mechanical metamaterials*, Science Robotics, 4, eaav7874, 2019.

[6]. Oliveira H. S., *et al.*, *Proprioceptive multistable mechanical metamaterial via soft capacitive sensors*, Smart Materials & Structures, 34, 035002, 2025.

[7]. Carton M., *et al.*, *Bridging hard and soft: torque-transmitting mechanical metamaterials*, Advanced Intelligent Systems, 6(7), 2400123, 2024.

[8]. Zhao L., *et al.*, *SoftSnap: rapid prototyping of untethered soft robots*, Soft Robotics, 11(5), p. 823-835, 2024.

[9]. Hiremath S., *3D-printed TPU pneumatic actuators for soft grippers*, Robomech Journal, 12:55, 2025.

[10]. Pishvar M., Harne R. L., *Active mechanical metamaterials for smart matter*, Advanced Science, 8(22), 2101440, 2021.

[11]. Liu C., *et al.*, *Programmable mechanical metamaterials: a review*, Frontiers in Materials, 11, 1452396, 2024.

[12]. Gregg C. E., *Ultralight, strong, and self-reprogrammable mechanical metamaterials*, Science Robotics, 9, eadi2746, 2024.

[13]. Surjadi J., *et al.*, *Double-network-inspired mechanical metamaterials*, Nature Materials, 24, p. 945-954, 2025.

[14]. Armentani E., *et al.*, *Vibro-Acoustic Numerical Analysis for the Chain Cover of a Car Engine*, Applied Sciences, 7(6), 2017.

[15]. Sakhaei B., *et al.*, *Vibration transfer path analysis for vehicle interiors*, Journal of Sound and Vibration, 482, 115472, 2020.

[16]. Wienen K., *et al.*, *Robust NVH engineering using experimental methods—source characterization techniques for component transfer path analysis and virtual acoustic prototyping*, SAE Technical Paper, 1, 2019-01-1542, 2019.

[17]. ***, *Altair Engineering, Transfer Path Analysis documentation*, OptiStruct User Guide, 2021.

[18]. Vasconcelos A. C. A., *et al.*, *Hybrid mechanical metamaterials: Advances of multi-functional mechanical metamaterials with simultaneous static and dynamic properties*, Heliyon, 11(3), e41985, 2025.

[19]. Hu Y., *et al.*, *Shape estimation for a TPU-based multi-material 3D printed soft pneumatic actuator using deep learning models*, Science China Technological Sciences, 67(5), p. 1470-1481, 2024.

[20]. de la Rosa S., *et al.*, *Design of customized TPU lattice structures for additive manufacturing: Influence on the functional properties in elastic products*, Polymers, 13(24), 4341, 2021.

[21]. Zhou Z., *et al.*, *Flexible strain sensors based on thermoplastic polyurethane fabricated by electrospinning: A review*, Sensors, 24, 4793, 2024.