ISSN 2522-9818 (print) *Сучасний стан наукових досліджень та технологій в промисловості. 2026. № 1 (35)*
ISSN 2524-2296 (online) *Innovative technologies and scientific solutions for industries. 2026. No. 1 (35)*

UDC 004.932.2 DOI: https://doi.org/10.30837/2522-9818.2026.1.154

Igor Nevlyudov, Olena Ruban, Dmytro Nikitin, Bogdan Misan, Oleksandr Iokhov

INVESTIGATION OF THE DAMPING PROPERTIES OF 3D-PRINTED LINERS WITH CONTROLLED PERFORATION

This study focuses on thermoplastic polyurethane (TPU) liners with controlled internal perforation intended for use in the "residual limb–liner–socket" system of lower-limb prostheses. The influence of material stiffness, hole geometry, and degree of perforation on vibration damping efficiency under impact–dynamic loading is investigated. **The aim of the** work is the experimental determination and optimization of the damping characteristics of TPU liners by varying material stiffness, hole shape, and perforation percentage using the free-decay vibration method. **Tasks**: to analyze the functional role of the liner as a damping element in the prosthetic system; to fabricate a series of 3D-printed TPU specimens with different stiffness levels, hole geometries, and perforation degrees; to implement an impact-based method for measuring free damped vibrations for each specimen; to determine the damping ratio and vibration attenuation percentage; to process experimental data in order to identify optimal combinations of material and geometric parameters; and to establish the relationships between material stiffness, perforation level, hole pattern, and the damping properties of liners. **Results**: a method for evaluating the damping characteristics of 3D-printed TPU liners with controlled internal structures was implemented and experimentally validated. A nonlinear dependence of vibration damping efficiency on the degree of perforation was identified, along with a systematic decrease in damping as TPU stiffness increased. It was shown that hexagonal hole geometry provides a more uniform deformation distribution and slightly higher damping efficiency compared to rhombic and triangular patterns. The obtained relationships enable targeted design of damping liners with an optimal balance between stiffness and vibration attenuation capacity. These findings support the solution of the following practical challenges: reduction of impact loads by decreasing peak dynamic forces transmitted from the prosthetic socket to the soft tissues of the residual limb; pressure redistribution through the formation of more uniform contact stresses at the skin–liner interface; improved user comfort by reducing vibration, pain, and skin irritation during walking; individual optimization through personalized selection of liner geometry and material based on body parameters, activity level, and tissue condition; and engineering design of structurally optimized components for biomedical applications. **Conclusions**: the study experimentally confirms the feasibility of controlling the damping properties of TPU liners by adjusting material stiffness, degree of perforation, and hole geometry. An optimal perforation range was identified for each TPU stiffness level, as well as the advantages of hexagonal perforation in terms of deformation uniformity and vibration damping efficiency.

Key words: TPU liners; 3D printing; material stiffness; prosthetics; impact testing.

Introduction

In lower limb prostheses, the mechanical interaction between the patient's residual limb and the rigid socket determines the level of comfort, gait stability, and long-term load tolerance. The central element of this interaction is the prosthetic liner (an elastic insert), which serves to cushion, redistribute pressure, and reduce shear stress in soft tissues. During walking, running, or descending stairs, the stump is subjected to impact and cyclic loads which, in the absence of effective damping, are transmitted directly to the tissues, causing pain, irritation, and microtrauma.

Modern liners are primarily made of silicone or polyurethane and have an almost solid structure. This approach provides basic elasticity but does not allow for targeted control of damping properties or adaptation to the patient's body weight, activity level, and anatomical characteristics. Additionally, solid polymer liners have limited breathability and do not ensure optimal stress distribution in the contact zone.

The use of 3D printing with thermoplastic polyurethane (TPU) allows for the creation of perforated, cellular structures in which properties are determined not only by the material's stiffness but also by the product's geometry. By changing the perforation pattern, stiffness, deformability, and energy dissipation capacity can be adjusted without replacing the material. This opens up the possibility of creating liners with controllable damping properties. The damping capability of TPU liners is determined by two mechanisms:

– viscoelastic losses in the TPU material;

– local deformations of the hole walls and the bridges between them.

As TPU stiffness decreases, internal friction and hysteresis increase, which enhances energy dissipation. At the same time, increasing the degree of perforation reduces the effective stiffness of the structure and amplifies bending and shear deformations, which also contributes to damping. However, excessive perforation leads to a loss of load-bearing capacity and a reduction in the efficiency of load transfer to the material, which can result in reduced vibration damping efficiency.

The shape of the holes determines the stress distribution and the nature of local deformations. Structures with more isotropic geometry (e.g., hexagonal) provide a more uniform distribution of deformations, whereas structures with sharp angles (triangular) create local stress concentrations, which may limit damping efficiency.

Analysis of Recent Studies and Publications

An analysis of existing approaches to cushioning liners in foot prosthesis designs demonstrates that the interface between the distal residual femur-tibia and the prosthetic socket is a critical area in terms of contact pressure distribution, shock load damping, and the prevention of local soft tissue trauma [1]. Liners traditionally serve as shock absorbers, i.e., they cushion impacts and distribute pressure generated during the foot's contact phase with the support surface, helping to reduce peak reaction forces and minimize the risk of pressure sores, pain, or skin damage during prolonged prosthesis use.

A recent systematic review demonstrates that liners made of elastomeric materials such as silicone or thermoplastic elastomers (TPU) are widely used to provide cushioning properties and user comfort, while their design and material properties influence the ability to evenly distribute peak pressure across the contact surface and reduce dynamic loads on the residual limb. An important indicator of the effectiveness of such interfaces is pressure distribution along the residual thigh-shin: clinical studies using pressure sensors indicate that the use of different liner materials can significantly alter the pressure profile, reducing peak values and increasing distribution uniformity, which, in turn, is associated with higher comfort scores and better tolerance for wearing the prosthesis [2, 3]. Despite the prevalence of commercial gel or polymer liners, traditional materials have a number of limitations: they often have limited capacity for controlled stiffness modulation, their mechanical properties may degrade under multi-cycle loading, and they do not always provide an optimal combination of cushioning with sufficient stability of the denture suspension, which can lead to increased shear stresses and discomfort.

Current research identifies two directions for improving the shock-absorbing function of liners: enhancing the material base through composite and hybrid materials, and structurally oriented approaches that allow for the control of stiffness and energy absorption distribution via geometric solutions, rather than solely through changes in material composition. Review articles emphasize that the development of new composite materials, including those based on thermoplastic, silicone, or polyurethane matrices, as well as combined systems with phase transitions or reinforcement, can provide better biomechanical adaptation to the contours of the residual limb and distribution of mechanical loads, in particular by reducing local pressure peaks, which is critical in areas of bony prominences [4]. Commercial solutions demonstrate that such materials provide increased flexibility and energy storage capacity, but questions regarding their durability, behavior under multi-cycle compression, and adaptation to various residual limb shapes remain the subject of active research.

Recently, the scientific community has focused on the implementation of bio-inspired metamaterials and cellular structures in the design of liners and sleeves, particularly using additive 3D printing technologies. Such structurally complex designs allow for the modification of local stiffness and energy absorption parameters, tailoring them to the anatomical features of the residual limb.

For example, a study demonstrates the use of auxetic metamaterials integrated into the liner and sleeve, resulting in a significant reduction in peak contact stresses by 60% to 65% compared to traditional silicone-elastomer solutions, as well as an increase in energy absorption capacity due to the specific geometry of the structure's cells [5]. This approach potentially allows not only for comfort and damping but also for the controlled distribution of stresses along the anatomical profile, which is critically important in personalized prosthetics.

However, although such structures with tunable parameters demonstrate significant advantages in laboratory testing and modeling, their clinical validation and standardized pressure assessments (e.g., contact pressure during walking, dynamic shear/friction profiles, tissue adaptation) require further research. Furthermore, reviews indicate a lack of data on the long-term behavior of such materials and structures in the context of cyclic

ISSN 2522-9818 (print) Сучасний стан наукових досліджень та технологій в промисловості. 2026. № 1 (35)
ISSN 2524-2296 (online) Innovative technologies and scientific solutions for industries. 2026. No. 1 (35)

loading, material aging, and changes in body mass and residual limb shape during prosthesis use [6]. Among the most important areas for future research are the development of standardized methods for assessing comfort and the mechanical properties of the "limb-liner-sleeve" interface, rigorous protocols for multifactorial experimental validation, and a shift toward individualized solutions based on the specific user's anatomical data.

This transition is key to optimizing the shock absorption of lower limb prosthesis liners and reducing the risk of secondary complications arising from excessive contact pressure or uneven mechanical loads.

Identification of Previously Unresolved Aspects of the Overall Problem. Purpose of the Work, Objectives

Designing damping TPU liners – in the simplest case, solid elastomeric liners with fixed stiffness – does not pose significant engineering complexity. However, the task becomes significantly more complex when using 3D-printed perforated structures, in which the damping properties are determined by the combined effect of several factors: the stiffness of the TPU material, the shape of the holes, and the degree of perforation.

Unlike solid liners, which do not allow for targeted control of vibration damping, perforated structures make it possible to alter damping properties by modifying the internal geometry. At the same time, this geometric freedom leads to the emergence of nonlinear and ambiguous relationships, under which perforation can either increase or decrease damping efficiency depending on the combination of parameters.

An analysis of scientific publications indicates that, to date, there is no unified method for selecting the degree of perforation and the shape of the holes for a given TPU stiffness that would ensure maximum damping of impact and vibration loads. Most studies focus either on the material properties of elastomers or on the geometry of structures, without a systematic combination of these factors and their experimental verification under impact-dynamic loading conditions. This necessitates further research aimed at developing engineering-based recommendations for the design of TPU liners with controllable damping properties.

The main objective of the study is the experimental determination and optimization of the damping properties of 3D-printed TPU liners by analyzing the influence of material stiffness, hole geometry, and degree of perforation under impact-dynamic loading conditions. To achieve this goal, the task was set to quantitatively establish the relationships between the liner's design parameters and its vibration damping efficiency. To solve this problem, the following is required:

– analyze the functional role of the liner in the prosthetic system;

– manufacture a series of 3D-printed samples made of TPU with varying stiffness and perforation parameters;

– implement an impact testing method to measure the free damped oscillations of the samples;

– determine the logarithmic decrement, damping coefficient, and percentage of vibration damping for each combination of parameters;

– process the obtained results to establish optimal values for stiffness, perforation density, and hole geometry.

The final result is the development of engineering-based recommendations for the design of TPU liners with controllable damping properties for use in lower limb prostheses.

Materials and Methods

The shape of the holes in the perforated structure of the shock-absorbing liner determines the nature of the redistribution of mechanical stresses, local deformations, and the propagation path of elastic waves in the polymer material, which directly affects the effectiveness of vibration damping. During an impact load, elastic waves arise in the material, which are repeatedly reflected, refracted, and partially scattered at the "material–void" boundaries, forming a complex pattern of wave interaction within the perforated structure (Fig. 1).

To ensure the controllability of the geometric parameters of perforation and the subsequent analysis of their impact on damping characteristics, it is advisable to use automated software tools with a graphical user interface (HMI) that allow for real-time modification of model parameters and the integration of experimental measurement results. Approaches to building such interfaces and implementing object-oriented automation algorithms are described in [7], which provides the basis for creating a software suite for controlling 3D printing parameters and analyzing vibration processes in liners with controlled perforation.

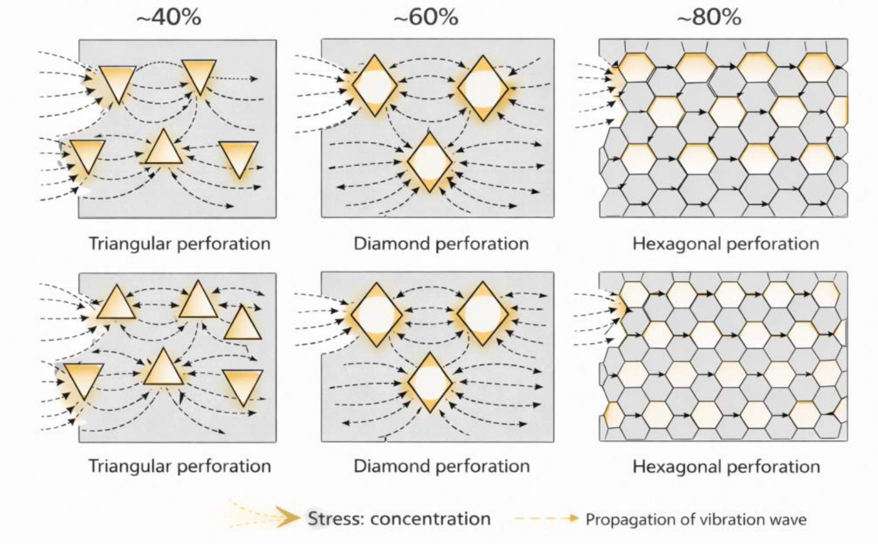


Fig. 1. Scheme of mechanical load distribution within the liner structure

Triangular apertures have sharp corners where stress concentrations occur. In these areas, waves are reflected unevenly, leading to a local increase in stiffness and a restriction of deformations. As a result, part of the mechanical energy is not converted into viscoelastic losses but is returned to the system in the form of reflected vibrations. This reduces the overall damping efficiency, especially for TPUs with increased stiffness [8].

Diamond holes have a more balanced geometry, which reduces local stress concentrations compared to triangular shapes. Wave propagation in such a structure is more uniform, though the presence of corners still leads to partial wave reflection. This provides an intermediate level of vibration damping, representing a compromise between triangular and hexagonal perforation.

Hexagonal holes form a quasi-isotropic cellular structure similar to honeycomb materials. With this geometry, mechanical waves propagate more uniformly in various directions, refract multiple times on the cell walls, and dissipate more effectively. This promotes intense shear deformations and increased internal viscoelastic energy losses, ensuring the highest vibration damping efficiency among the considered shapes [9].

To evaluate the damping properties, the free damped oscillation method (impact method) was applied. This method is the standard for rapid evaluation of viscoelastic materials and allows the logarithmic decay rate to be determined without the use of complex vibration test bench equipment. The essence of the method lies in recording the damped oscillations of a mechanical system excited by a short-term impulse load, followed by an analysis of the rate of decrease in oscillation amplitude over time [10]. The method is particularly effective for studying elements with pronounced viscoelastic properties, which include polymer materials such as TPU. The operating principle of the test rig for impact testing of samples and the test rig developed according to this scheme are shown in Fig. 2.

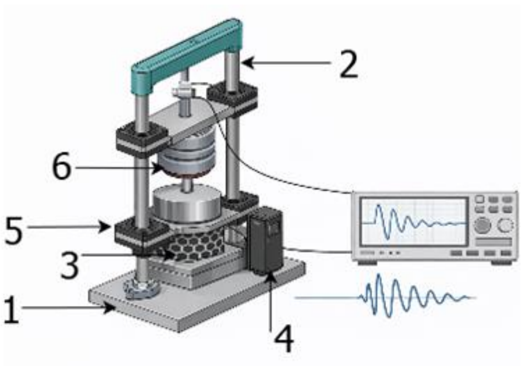


Fig. 2. Operating principle of the model for impact testing of samples: 1 – model base; 2 – guide for the impact hammer; 3 – test sample; 4 – accelerometer sensor block; 5 – impact platform; 6 – impact hammer

ISSN 2522-9818 (print) Сучасний стан наукових досліджень та технологій в промисловості. 2026. № 1 (35)
ISSN 2524-2296 (online) Innovative technologies and scientific solutions for industries. 2026. No. 1 (35)

The setup consists of a massive, rigid base (weighing 20 kg) on which the test specimen is mounted. An inertial mass (weighing 2.5 kg) is placed on top of the specimen. The system constitutes a classical oscillator with a single degree of freedom.

The oscillations were excited by a calibrated vertical impact on the center of the inertial load, which ensured the reproducibility of the initial experimental conditions. The system's response was recorded by a piezoelectric accelerometer with a sensitivity of 100 mV/g; its signal was fed to an analog-to-digital converter for subsequent digital processing. A sampling rate of 10 kHz provided sufficient temporal resolution for analyzing transient processes and accurately determining damping parameters.

The approach to experimental verification and processing of measurement signals is based on the principles of automated control of dynamic parameters, similar to those presented in [11], where the feasibility of using digital recording and mathematical modeling for evaluating the characteristics of technical systems was confirmed. After impact excitation, the system's motion was approximated by a model of a single-mass mechanical system with viscous damping, for which the amplitude of oscillations decreases exponentially over time. This model allows determining the damping coefficient and the logarithmic decay rate, which are key parameters for evaluating the effectiveness of 3D-printed liners with controlled perforation.

This approach allows for a direct assessment of how effectively the liner reduces oscillations and is convenient for engineering interpretation and comparative analysis of different design variants. To ensure comparability of results, tests of all samples were performed using a standardized algorithm that included the following steps:

– Sample positioning: The TPU liner under study was placed in the test bench's working area, ensuring centering between the rigid support plate and the inertial mass.

– Installation of the measurement system: The accelerometer was rigidly fixed to the load surface, after which the reliability of the mounting was checked to avoid signal distortion.

– Excitation of vibrations: The system was brought out of equilibrium by applying a single vertical impact with controlled energy (impulse load).

– Data acquisition: The time-domain signal of the vibration acceleration *a(t)* was recorded using an ADC.

– Signal analysis: The amplitude values of successive peaks of the decaying oscillations were identified.

– Calculation of characteristics: Based on the obtained data, the logarithmic decrement, damping coefficient, and vibration damping efficiency index were calculated.

For several successive oscillation peaks $x_1, x_2, x_3, \ldots, xn$, the decay rate is described by the logarithmic decrement [12,13].

The logarithmic decrement over several periods is determined by the formula:

$$\delta = \frac{1}{N} ln\left(\frac{x_1}{x_{N+1}}\right) \quad (1)$$

where N is the number of periods between the measured peaks.

The ratio of adjacent peaks:

$$r = \frac{x_{n+1}}{x_n} = 1 - \frac{D}{100\%} \quad (2)$$

where D – vibration damping ratio, %.

For small and moderate damping values, the damping coefficient ζ can be determined using an approximate formula:

$$\zeta \approx \frac{\delta}{2\pi} \quad (5)$$

To provide a clear comparison of the effectiveness of various TPU gaskets in operation, a vibration damping coefficient expressed as a percentage has been introduced, which indicates the relative reduction in vibration amplitude over a single cycle:

$$D = \left(1 - \frac{x_{n+1}}{x_n}\right) \cdot 100\% \quad (4)$$

The automated control system (ACS) for filtering noise from the accelerometer when measuring the vibrations of a test specimen will consist of the following blocks, Fig. 3.

The developed automated control system suppresses external noise and extracts the informative component of the accelerometer signal, which corresponds to free damped oscillations following an impact excitation.

At the system input, an acceleration signal a(t) is formed, to which external noise (measurement, mechanical, and electronic) is added, modeled as an additive random process. The resulting signal *a(t)+n(t)* is fed to the input of the measurement path [14–16].

The overall transfer function of the accelerometer signal processing channel can be expressed as:

$$W_{(s)} = W_s(s) \cdot W_{DAQ}(s) \cdot W_f(s) \quad (5)$$

where $W_s(s)$ – transfer function of an accelerometer, $W_{DAQ}(s)$ – transfer function of the measurement path, $W_f(s)$ – transfer function of the filter.

Сучасний стан наукових досліджень та технологій в промисловості. 2026. № 1 (35)
ISSN 2522-9818 (print)
Innovative technologies and scientific solutions for industries. 2026. No. 1 (35)
ISSN 2524-2296 (online)

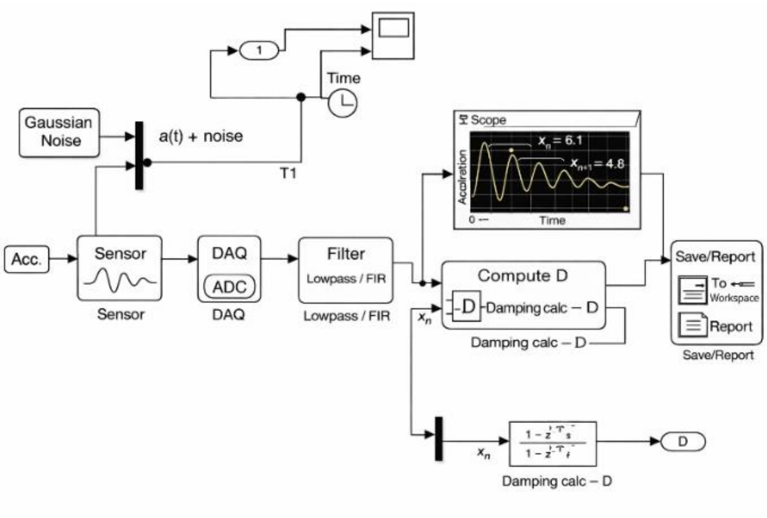


Fig. 3. Accelerometer signal processing

The transfer function of the accelerometer can be described, in a first approximation, as a first-order aperiodic system:

$$W_s(s) = \frac{K_S}{T_S s+1}, \qquad (6)$$

where *Ks* – accelerometer sensitivity coefficient, *Ts* – time constant.

The transfer function of a low-pass filter designed to suppress noise in the system will take the following form:

$$W_f(s) = \frac{1}{T_f s+1} \qquad (7)$$

where T_f – the filter time constant, which determines the cutoff frequency.

This transfer function of the digital filter smooths out the high-frequency noise components of the accelerometer's acceleration signal while preserving the system's primary low-frequency dynamics, which are necessary for the accurate determination of the test specimen's vibration damping parameters. A similar approach to numerical modeling and algorithmic processing of measured electrical sensor signals is described in [17], where the effectiveness of using digital filtering methods to improve the accuracy of experimental studies of dynamic systems is demonstrated.

To minimize experimental error, each measurement was repeated at least three times for each sample configuration, followed by statistical averaging of the results. This approach reduces the influence of random signal fluctuations and ensures the reproducibility of the obtained data.

The use of the impulse method (free oscillation method) in this study is due to its high information content, ease of implementation, and the ability to quickly determine damping characteristics without the need for complex excitation equipment. In combination with digital signal processing, this method provides a reliable estimate of the damping coefficient and the logarithmic decay factor.

First and foremost, the method is easily implemented in laboratory conditions without the use of complex electrodynamic vibration test benches; it also allows for the rapid comparative analysis of a large number of samples within a short period of time. Furthermore, it does not require significant energy consumption or expensive equipment. At the same time, the limitations of the method were taken into account when interpreting the results.

These include dependence on initial conditions: response parameters may vary depending on the impact force and the magnitude of the static preload; the specifics of the mode: the obtained characteristics describe energy dissipation in the mode of free damped oscillations, which may differ from the material's behavior under steady-state harmonic excitation; processing requirements: the accuracy of the results significantly depends on the quality of the signal filtering and peak detection algorithms.

Research Results and Discussion

To investigate the influence of structural and material parameters of printed TPU spacers on vibration damping efficiency, ranges of variation for key factors were determined, taking into account operating conditions and the capabilities of FFF/FDM technology.

Polymer stiffness was selected as the primary material factor.

ISSN 2522-9818 (print) Сучасний стан наукових досліджень та технологій в промисловості. 2026. № 1 (35)
ISSN 2524-2296 (online) Innovative technologies and scientific solutions for industries. 2026. No. 1 (35)

The study utilized TPU with different Shore A hardness values, specifically:

– 50A, a high-stiffness elastomer characterized by lower deformability and reduced internal energy losses;

– 80A, a medium-hardness elastomer with a balanced ratio of stiffness and damping properties;

– 90A, a low-hardness elastomer characterized by increased deformability and significant viscoelastic energy losses.

For the convenience of conducting the experiment, samples of different hardness will be printed in different colors (Fig. 4).

a) b) c)

Fig. 4. Images of three products with different hardnesses on the Shore A. scale: a) sample with a hardness of 50A; b) sample with a hardness of 80A; c) sample with a hardness of 90A

The second parameter is the perforation ratio *P*, which defines the ratio of the area of the holes to the total cross-sectional area. The range under investigation: 40% – preservation of high effective stiffness; 60% – expected optimum damping; 80% – significant reduction in structural stiffness.

The selected range of values allows us to trace the nonlinear relationship between the liner's damping properties and its deformation capacity, and additionally to identify the optimal perforation parameters for materials of varying stiffness. Examples of sample perforation are shown in Fig. 5.

a) b) c)

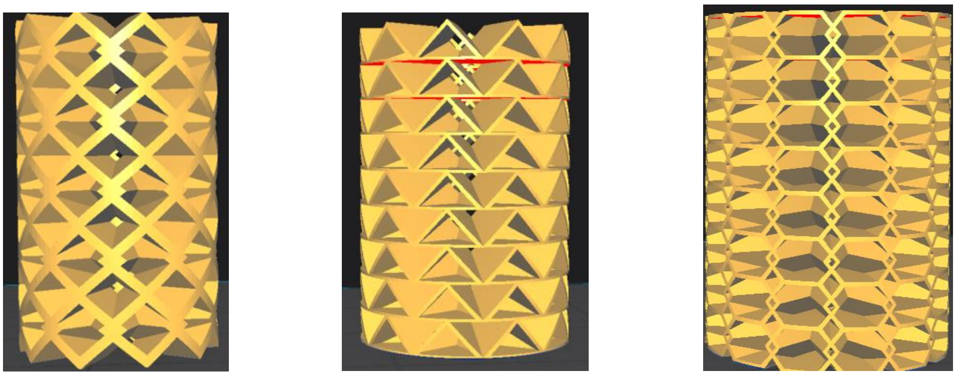
Fig. 6. Examples of different perforation percentages: a) sample with a 40% perforation rate; b) sample with a 60% perforation rate; c) sample with an 80% perforation rate

The third factor is the topology of the cells (perforation shape): Triangular: characterized by local stress concentration; Diamond: an intermediate option with moderate anisotropy; Hexagonal: provides the most uniform distribution of deformations. A comparative analysis of the proposed shapes allows us to assess the sensitivity of the damping properties to changes in the hole contour when other determining parameters (stiffness and perforation percentage) remain constant. Examples of perforation patterns are shown in Fig. 7.

To eliminate the dimensional factor, all samples were cylindrical in shape (diameter 40 mm, height 60 mm). The experimental design included a sample of 45 specimens to characterize nonlinear effects [18]. The results of the study are presented in Table 1.

The results of the full sample of 45 samples are presented graphically in Fig. 8.

Сучасний стан наукових досліджень та технологій в промисловості. 2026. № 1 (35) *ISSN 2522-9818 (print)*
Innovative technologies and scientific solutions for industries. 2026. No. 1 (35) *ISSN 2524-2296 (online)*

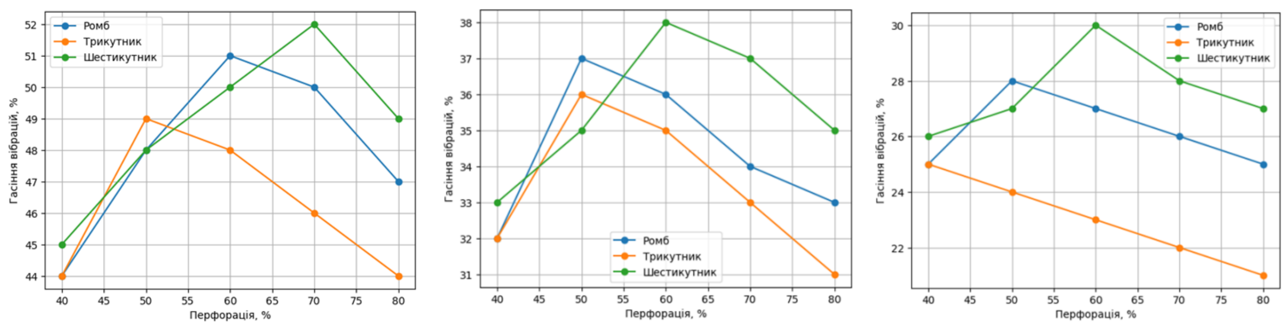


a) b) c)

Fig. 7. Examples of different perforation percentages: a) diamond-shaped perforation; b) triangular perforation; c) hexagonal perforation

Table 1. *Research results*

№	TPU	Shape	Perforation rate, %	*D*,%	№	TPU	Shape	Perforation rate, %	*D*,%
1	50A	Diamond	40	44	24	80A	Triangular	70	33
2	50A	Diamond	50	48	25	80A	Triangular	80	31
3	50A	Diamond	60	51	26	80A	Hexagon	40	33
4	50A	Diamond	70	50	27	80A	Hexagon	50	35
5	50A	Diamond	80	47	28	80A	Hexagon	60	38
6	50A	Triangular	40	44	29	80A	Hexagon	70	37
7	50A	Triangular	50	49	30	80A	Hexagon	80	35
8	50A	Triangular	60	48	31	90A	Diamond	40	25
9	50A	Triangular	70	46	32	90A	Diamond	50	28
10	50A	Triangular	80	44	33	90A	Diamond	60	27
11	50A	Hexagonal	40	45	34	90A	Diamond	70	26
12	50A	Hexagonal	50	48	35	90A	Diamond	80	25
13	50A	Hexagonal	60	50	36	90A	Triangular	40	25
14	50A	Hexagonal	70	52	37	90A	Triangular	50	24
15	50A	Hexagonal	80	49	38	90A	Triangular	60	23
16	80A	Hexagonal	40	32	39	90A	Triangular	70	22
17	80A	Diamond	50	37	40	90A	Triangular	80	21
18	80A	Diamond	60	36	41	90A	Hexagonal	40	26
19	80A	Diamond	70	34	42	90A	Hexagonal	50	27
20	80A	Diamond	80	33	43	90A	Hexagonal	60	30
21	80A	Diamond	40	32	44	90A	Hexagonal	70	28
22	80A	Triangular	50	36	45	90A	Hexagonal	80	27
23	80A	Triangular	60	35					



a) b) c)

Fig. 8. Research results: a) vibration damping of perforated TPU gaskets with a stiffness of 50A; b) vibration damping of perforated TPU gaskets with a stiffness of 80A; c) vibration damping of perforated TPU gaskets with a stiffness of 90A

ISSN 2522-9818 (print) Сучасний стан наукових досліджень та технологій в промисловості. 2026. № 1 (35)
ISSN 2524-2296 (online) Innovative technologies and scientific solutions for industries. 2026. No. 1 (35)

Analysis of the experimental results showed that the key factor in the effectiveness of vibration damping by TPU gaskets is the material's stiffness. An increase in stiffness from 50A to 90A is accompanied by a steady decrease in the damping level.

Specifically:

– for TPU 50A, the maximum damping efficiency reaches approximately 52%;

– for TPU 80A — about 39%;

– for TPU 90A — does not exceed 31%.

This trend is due to a decrease in internal energy dissipation in stiffer elastomers, as well as an increase in the effective stiffness of the "support–pad–load" system, which limits the deformation of the damping element and, accordingly, reduces the level of energy dissipation.

For all investigated TPU stiffness values, a nonlinear dependence of damping on the degree of perforation was observed. Increasing perforation from 40% to a certain optimum leads to an increase in damping properties, while a further increase in perforation causes them to decrease. At the same time, the position of the damping maximum depends on the material stiffness:

– for TPU 50A, the optimal perforation range is 60–70%;

– for TPU 80A, 50–60%;

– for TPU 90A, 40–60%.

The obtained data indicate that as material stiffness increases, the optimal perforation level shifts toward lower values, since excessive weakening of the structure of stiff samples leads to a loss of contact stability and a decrease in damping capacity.

The perforation geometry has a secondary but reproducible effect on vibration damping. The analysis reveals the following trends:

– triangular holes provide maximum damping at lower perforation levels (40–50%), which is associated with stress concentration at the vertices and local deformation confinement;

– Diamond geometry is optimal at medium perforation levels (approximately 60%);

– the hexagonal structure demonstrates the highest damping values at higher perforation levels (60–70%) due to a more uniform distribution of stresses and deformations in the material.

Differences between the shapes typically do not exceed 2–3%, confirming their corrective rather than determining role compared to material parameters.

An analysis of 45 parameter combinations showed that the effectiveness of vibration damping by TPU gaskets is determined by the combined action of three factors: material stiffness, degree of perforation, and hole geometry. Changing any one of these factors in isolation does not ensure maximum damping, indicating the need for comprehensive design optimization that takes into account both material and geometric characteristics.

As a result, it was established that the highest level of vibration damping is achieved for soft TPU gaskets with an optimally selected degree of perforation. As material stiffness increases, the optimal perforation values shift toward lower values, while the shape of the holes serves as a tool for fine-tuning the damping properties. The obtained patterns can be used in the design of damping elements for additively manufactured machine and mechanism components.

To identify the patterns of influence of physical-mechanical and geometric parameters on the vibration-damping effectiveness of TPU gaskets manufactured using additive technologies, correlation-regression analysis methods were applied. The key objective of this stage was to establish a quantitative relationship between the design features of the samples and their ability to reduce vibration amplitude. To optimize the research process and reduce the number of required measurements without losing statistical reliability, a multivariate experimental design was used instead of a full search of all possible combinations of factor levels. This approach involved selecting representative points within the studied range, which allowed for the construction of an adequate model based on a limited data sample.

The factorial space of the experiment was formed by the following independent variables:

– TPU material hardness on the Shore A scale (50, 80, 90);

– degree of gasket perforation, % (from 40% to 80% in 10% increments);

– perforation shape (Diamond, triangular, hexagonal);

– amplitude of free-mode vibrations after impact excitation;

– vibration damping percentage D.

The obtained values were used to calculate Pearson correlation coefficients and construct multivariate regression models.

To perform calculations in the IBM SPSS Statistics software environment, all variables were converted to numerical form and coded as follows:

– material hardness (Hardness);

– degree of perforation (Perforation), %;

– perforation shape (Shape): 2 – triangular; 1 – diamond; 3 – hexagonal;

Сучасний стан наукових досліджень та технологій в промисловості. 2026. № 1 (35) *ISSN 2522-9818 (print)*
Innovative technologies and scientific solutions for industries. 2026. No. 1 (35) *ISSN 2524-2296 (online)*

– vibration damping (Damping), %.

To mathematically describe the influence of input parameters on the damping capacity of the gaskets, a multiple linear regression model was selected:

$$D = b_0 + b_1 H + b_2 P + b_3 S + \varepsilon \quad (5)$$

where *D* – vibration damping percentage; *H* – material hardness TPU; *P* – perforation degree, %; *S* – perforation shape; b_0, b_1, b_2, b_3 – regression coefficients; ε – random model error.

A quality check of the resulting model using the Model Summary module demonstrated high adequacy. The coefficient of determination $R2$ is 0.916, which means that the constructed model explains over 91.6% of the variation in the experimental data [19, 20]. The adjusted coefficient of determination $R2$ also exceeds the threshold of 0.91, confirming the presence of a strong and stable correlation between the selected design parameters of the liners and their damping properties. The results of the quality check are shown in Fig. 9.

Model Summary

					Change Statistics				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	R Square Change	F Change	df1	df2	Sig. F Change
1	,957[a]	,916	,910	2,845	,916	148,467	3	41	,000

a. Predictors: (Constant), Perforation, Shape, Hardness

Fig. 9. Model Summary

An ANOVA table was used to test the hypothesis regarding the statistical significance of the constructed regression model. In all cases, the significance level Sig. < 0.05, which indicates the reliability of the results obtained and allows us to reject the null hypothesis regarding the absence of an effect of the studied parameters. The results of the ANOVA significance calculations are presented in Fig. 10.

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	3605,730	3	1201,910	148,467	,000[b]
	Residual	331,915	41	8,095		
	Total	3937,644	44			

a. Dependent Variable: Damping

b. Predictors: (Constant), Perforation, Shape, Hardness

Fig. 10. Results of the ANOVA significance test

To rank the input parameters according to their degree of influence on the liner's integral energy dissipation capacity, an analysis of standardized regression coefficients ("β-coefficients") was conducted [21]. A comparison of the absolute values of these indicators allowed us to establish a hierarchy of factor influence:

– material hardness: acts as the dominant factor in the model. The highest absolute value of the β-coefficient indicates that it is the physical and mechanical properties of the polymer matrix that are decisive for vibration damping efficiency.

– degree of perforation: has a significant effect on damping characteristics; however, the nature of this effect is complex and likely nonlinear, reflecting changes in the structural stiffness of the sample.

– cell topology: is characterized by the lowest coefficient value, indicating its auxiliary role. The shape of the holes serves to "fine-tune" (adjust) the product's properties, ranking significantly lower in importance than material hardness and perforation density. The results of the influence of the liner's perforation parameters are presented as Pearson correlations and shown in Fig. 11.

Correlations

		Damping	Hardness	Shape	Perforation
Pearson Correlation	Damping	1,000	-,956	,049	,013
	Hardness	-,956	1,000	,000	,000
	Shape	,049	,000	1,000	,000
	Perforation	,013	,000	,000	1,000
Sig. (1-tailed)	Damping	.	,000	,373	,465
	Hardness	,000	.	,500	,500
	Shape	,373	,500	.	,500
	Perforation	,465	,500	,500	.
N	Damping	45	45	45	45
	Hardness	45	45	45	45
	Shape	45	45	45	45
	Perforation	45	45	45	45

Fig. 11. Pearson correlation

ISSN 2522-9818 (print) Сучасний стан наукових досліджень та технологій в промисловості. 2026. № 1 (35)
ISSN 2524-2296 (online) Innovative technologies and scientific solutions for industries. 2026. No. 1 (35)

Conclusions

The stiffness of the TPU material, the degree of perforation, and the shape of the holes significantly affect the vibration damping efficiency of additively manufactured gaskets. The experimental dependencies obtained show that the damping properties result from the interaction between the viscoelastic characteristics of the material and the geometry of the gasket's internal structure. An excessive increase in material stiffness or the degree of perforation leads to a decrease in damping due to a reduction in deformation capacity and a loss of contact stability in the system.

It has been established that for each stiffness value, there is an optimal degree of perforation that ensures maximum vibration damping. For soft TPU 50A, the optimum lies in the range of 60–70%; for medium-stiffness 80A materials, from 50% to 60%; and for stiff TPU 90A, from 40% to 60%. Thus, as material stiffness increases, the optimal perforation level systematically shifts toward lower values.

The shape of the perforation affects the distribution of stresses and strains in the material and, accordingly, the level of damping; however, its influence is secondary compared to the material parameters. Hexagonal perforation provides a more uniform stress distribution and demonstrates slightly higher damping values; Diamond perforation occupies an intermediate position; and triangular perforation is characterized by lower efficiency due to stress concentration at the vertices of the holes. The difference between the shapes does not exceed 2–3%, which allows us to consider hole geometry as a fine-tuning tool rather than a determining parameter.

Based on the results of the study, the following tasks were accomplished:

– the influence of TPU stiffness on the damping properties of the gaskets was analyzed;

– the dependence of vibration damping on the degree of perforation for various materials was investigated;

– the influence of hole geometry on stress distribution and damping efficiency was evaluated;

– a regression-correlation analysis was performed and a multifactorial model was constructed describing the influence of structural and material parameters on vibration damping.

The constructed regression model showed that over 91% of the variation in damping level is explained by the combined effect of material stiffness, the degree of perforation, and the shape of the holes. TPU stiffness makes the largest contribution; the degree of perforation has a significant but nonlinear effect, while the shape of the holes plays a moderating role.

Further research should focus on analyzing the damping properties of 3D-printed TPU insoles under various frequency loading conditions and cyclic fatigue typical of real-world walking. It is promising to study the influence of the anisotropy of additively manufactured structures, printing parameters, and external factors (temperature, humidity) on the viscoelastic behavior of the material. Combining experimental results with numerical modeling and optimization methods will allow for the automated selection of perforation parameters tailored to the individual characteristics of the prosthesis user and enhance the effectiveness of personalized shock-absorbing solutions.

Thus, to achieve maximum vibration damping, comprehensive optimization of the TPU insert design is required, taking into account both the material properties and the geometry of the internal structure. The results obtained can be used in the design of shock-absorbing and vibration-damping elements for additively manufactured machine and mechanism components, particularly in systems where effective absorption of dynamic loads is required within limited dimensions and mass.

Conflict of interest

The authors declare that they have no conflicts of interest, including financial, personal, authorial, or any other nature, that could influence the research or the results published in this article.

Funding

The study was conducted without financial support.

Data availability

Data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies to write this paper.

References

1. Ahn, S.J., Lee, H. and Cho, K.-J. (2024), "3D printing with a 3D printed digital material filament for programming functional gradients", *Nature Communications*, Vol. 15, 3605 p. DOI: https://doi.org/10.1038/s41467-024-47480-5
2. Wang, Y., Tan, Q., Pu, F., Boone, D.A. and Zhang, M. (2020)"A review of the application of additive manufacturing in prosthetic and orthotic clinics from a biomechanical perspective", *Engineering*, Vol. 6 (11), pp. 1258-1266. DOI: https://doi.org/10.1016/j.eng.2020.07.019
3. Baldock, M., Pickard, N., Prince, M., Kirkwood, S., Chadwell, A., Howard, D., Dickinson, A., Kenney, L., Gill, N., Curtin, S. (2023), "Adjustable prosthetic sockets: A systematic review of industrial and research design characteristics and their justifications", *Journal of NeuroEngineering and Rehabilitation*, Vol. 20, 147 p. DOI: https://doi.org/10.1186/s12984-023-01270-0
4. Nevliudov, I., Yevsieiev, V., Maksymova, S., Chala, O., (2023), "A Small-Sized Robot Prototype Development Using 3D Printing", *CAD In Machinery Design Implementation and Educational Issues (CADMD'2023): proceedings of the XXXI International Conference*. (Conference in memory of Professor Jerry Wrobel), Suprasl, 26-28 October, 2023. Suprasl, 2023. 12 p.
5. Xie J., Liu X., Tang J., Li X., Li W., (2021), "Study on friction behavior at the interface between prosthetic socket and liner", *Acta of Bioengineering and Biomechanics*, Vol. 23, No. 1. P. 83–93. DOI: https://doi.org/10.37190/ABB-01751-2020-04
6. Rossi, S.; Puglisi, A.; Benaglia, M., (2018) "Additive Manufacturing Technologies: 3D Printing in Organic Synthesis". *ChemCatChem*, Vol. 10, (7), pp. 1512– 1525. DOI: https://doi.org/10.1002/cctc.201701619.
7. Syed, K. M., Yevsieiev, V., Nevliudov, I, Lyashenko, V, Adel, R. A., Wahid, R. (2022), "HMI Development Automation with GUI Elements for Object-Oriented Programming Languages Implementation," *International Journal of Engineering Trends and Technology (IJETT)*, Vol. 70, No. 1, pp. 139-145. DOI: https://doi.org/10.14445/22315381/IJETT-V70I1P215
8. Hassan Beygi, B., Wong, M.S. (2023), "Contemporary and future development of 3D printing technology in the field of assistive technology, orthotics and prosthetics", *Canadian Prosthetics & Orthotics Journal*, 6(2), 42225. DOI: https://doi.org/10.33137/cpoj.v6i2.42225
9. Devin, K.M., Tang, J., Hamilton, A.R., Moser, D. and Jiang, L. (2024), "Assessment of 3D-printed mechanical metamaterials for prosthetic liners", *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*, 238(3), 348-357. DOI: https://doi.org/10.1177/09544119231225529
10. Nikitin, D. O., Nevlyudov, I. Sh., Zharikova, I. V., Bronnikov, A. I., Strilets, R. E. (2025), " Devising of a method for controlling products during photopolymer 3D printing". *Eastern-European Journal of Enterprise Technologies*, 4(1 (136), pp. 42–54. DOI: https://doi.org/10.15587/1729-4061.2025.335706
11. Sh. Nevlyudov, S.P. Novoselov, A.G. Resnichenko. (2012), "Experimental verification of theoretical foundations making the basis of the substrate roughness surface automated control technology". Telecommunications and Radio Engineering, 71(19), pp. 1791-1799. DOI: https://doi.org/10.1615/TelecomRadEng.v71.i19.80
12. Plesec, V., Hanželič, B. and Harih, G. (2024), "Development of a metamaterial numerical model for improving 3D-printed lower-limb prosthetic liners", *Human Systems Engineering and Design (IHSED 2024): Future Trends and Applications*, 158, pp. 228–238. DOI: https://doi.org/10.54941/ahfe1005546
13. Gritsyuk, V., Nevliudov, I., Zablodskiy, M. and Subramanian, P. (2022), "Estimation of eddy currents and power losses in the rotor of a screw electrothermomechanical converter for additive manufacturing", *Machinery and Energetics*, 13(2), pp. 41–49. DOI: https://doi.org/10.31548/machenergy.13(2).2022.41-49
14. Andriën, A.R.P., Guerreiro Tomé Antunes, D.J., van de Molengraft, M.J.G. and Heemels, W.P.M.H. (2018) "Similarity-based adaptive complementary filter for IMU fusion", *2018 European Control Conference (ECC)*, pp. 3044-3049. DOI: https://doi.org/10.23919/ECC.2018.8550358
15. Justa, J., Šmídl, V. and Hamáček, A. (2020) "Fast AHRS Filter for Accelerometer, Magnetometer, and Gyroscope Combination with Separated Sensor Corrections", *Sensors*, 20(14), 3824 p. DOI: https://doi.org/10.3390/s20143824
16. Osadchyi S. I., Zozulya, V. A., Kalich, V. M., Timoshenko, A. S. (2024), "The frequency method for optimal identification of close-loop system elements". *Radio Electronics, Computer Science, Control*, (4), 195 p. DOI: https://doi.org/10.15588/1607-3274-2023-4-18
17. Mamalis, A.G., Nevliudov, I., Romashov, Yu. (2021), "An approach for numerical simulating and processing of measured electrical signals from board sensors installed on wheeled electro-mechanical platforms", *Journal of Instrumentation*, 16(10), 10006 p. DOI: https://doi.org/10.1088/1748-0221/16/10/P10006
18. Rudenko, O., Bezsonov, O., Ilyunin, O., Demirskiy, O., Serdiuk, N., Arsenyeva, O., Semenenko, O. (2023), "Using a Neural Network Approach to Predict Deposits on the Surfaces of Heat Exchange Equipment", *Chemical Engineering Transactions*, 103, pp. 697-702. DOI: https://doi.org/10.3303/CET23103117
19. Brian, H., Daniel, T. (2017), *Essential MATLAB for Engineers and Scientists*, Academic Press, 411 p. DOI: https://doi.org/10.1016/C2015-0-02182-7

ISSN 2522-9818 (print) *Сучасний стан наукових досліджень та технологій в промисловості. 2026. № 1 (35)*
ISSN 2524-2296 (online) *Innovative technologies and scientific solutions for industries. 2026. No. 1 (35)*

20. Han, S., Bhattacharyya, S. P. (2018), "PID controller synthesis using a v-Hurwitz stability criterion", *IEEE Control Syst. Lett.*, Vol. 2, No. 3, pp. 525-530. DOI: https://doi.org/10.1109/LCSYS.2018.2842784
21. *Statistical Methods in Psychiatry Research and SPSS.* 2nd Edition, ByM. Venkataswamy Reddy. Apple Academic Press. 2019. 442 p. DOI: https://doi.org/10.1201/9780429023309

Received (Надійшла) 26.01.2026
Accepted for publication (Прийнята до друку) 14.03.2026
Publication date (Дата публікації) 30.03.2026

Відомості про авторів / About the Authors

Невлюдов Ігор Шакірович – доктор технічних наук, професор, заслужений діяч науки і техніки України, Лауреат Державної премії в галузі науки і техніки України; Лауреат Державної премії України в галузі освіти, Харківський національний університет радіоелектроніки, завідувач кафедри комп'ютерно-інтегрованих технологій, автоматизації, робототехніки та безпекової інженерії; м. Харків, Україна;
Igor Nevlyudov – Doctor of Technical Sciences, Professor, Honored Worker of Science and Technology of Ukraine, Laureate of the State Prize in Science and Technology of Ukraine; Laureate of the State Prize of Ukraine in the field of education, Kharkiv National University of Radio Electronics, Head of the Department of Computer Integrated Technologies, Automation, Robotics and Safety Engineering; Kharkiv, Ukraine;
e-mail: igor.nevliudov@nure.ua
ORCID ID: https://orcid.org/0000-0002-9837-2309
Scopus Author ID: https://www.scopus.com/authid/detail.uri?authorId=57216434058

Рубан Олена Анатоліївна – доктор фармацевтичних наук, професор, Національний фармацевтичний університет, завідувачка кафедри заводської технології ліків та косметичних засобів; м. Харків, Україна;
Olena Ruban – Doctor of Pharmaceutical Sciences, Professor, National University of Pharmacy, Head of the Department of Industrial Technology of Medicines and Cosmetics; Kharkiv, Ukraine;
e-mail: Ruban_elen@ukr.net
ORCID ID: https://orcid.org/0000-0002-2456-8210
Scopus Author ID: https://www.scopus.com/authid/detail.uri?authorId=55976080800

Нікітін Дмитро Олександрович – кандидат технічних наук, Харківський національний університет радіоелектроніки, доцент кафедри комп'ютерно-інтегрованих технологій, автоматизації, робототехніки та безпекової інженерії; м. Харків, Україна;
Dmytro Nikitin – Candidate of Technical Sciences, Kharkiv National University of Radio Electronics, Associate Professor of the Department of Computer Integrated Technologies, Automation, Robotics and Safety Engineering; Kharkiv, Ukraine;
e-mail: dmytro.nikitin@nure.ua
ORCID ID: https://orcid.org/0000-0003-4388-4996
Scopus Author ID: https://www.scopus.com/authid/detail.uri?authorId=59412787100&origin=recordpage#

Місан Богдан Сергійович – аспірант, Харківський національний університет радіоелектроніки, кафедра комп'ютерно-інтегрованих технологій, автоматизації, робототехніки та безпекової інженерії; м. Харків, Україна;
Bogdan Misan PhD Student, Kharkiv National University of Radio Electronics, Department of Computer Integrated Technologies, Automation, Robotics and Safety Engineering; Kharkiv, Ukraine;
e-mail: bohdan.misan@nure.ua
ORCID ID: https://orcid.org/0009-0007-4905-9280

Іохов Олександр Юрійович – доктор технічних наук, професор, Національна академія Національної гвардії України, начальник центру імітаційного моделювання; Харків, Україна;
Oleksandr Iokhov – Doctor of Technical Sciences, Professor, National Academy of the National Guard of Ukraine, Head of the Simulation Modeling Center; Kharkiv, Ukraine;.
e-mail: iohov@ukr.net;
ORCID: ID: https://orcid.org/0000-0002-1718-0138
Scopus ID: https://www.scopus.com/authid/detail.uri?authorId=57220574439

Сучасний стан наукових досліджень та технологій в промисловості. 2026. № 1 (35) *ISSN 2522-9818 (print)*
Innovative technologies and scientific solutions for industries. 2026. No. 1 (35) *ISSN 2524-2296 (online)*

ДОСЛІДЖЕННЯ ДЕМПФУВАЛЬНИХ ВЛАСТИВОСТЕЙ 3D-ДРУКОВАНИХ ЛАЙНЕРІВ З КЕРОВАНОЮ ПЕРФОРАЦІЄЮ

Предметом дослідження цієї статті є демпфувальні властивості 3D-друкованих прокладок (лайнерів) з термопластичного поліуретану (TPU) з керованою внутрішньою перфорацією, призначених для використання в системі «кукса – лайнер – гільза» у протезах нижніх кінцівок. Досліджується вплив жорсткості матеріалу, геометрії отворів та ступеня перфорації на ефективність гасіння вібрацій при ударно-динамічному навантаженні. **Мета** роботи – експериментальне визначення та оптимізація демпфувальних характеристик TPU-лайнерів шляхом варіювання жорсткості матеріалу, форми отворів і відсотка перфорації з використанням методу вільних затухаючих коливань. **Завдання**: проаналізувати функціональну роль лайнера як демпфуального елемента у протезній системі; Виготовити серію 3D-друкованих TPU-зразків з різною жорсткістю, геометрією отворів та ступенем перфорації; реалізувати ударний метод вимірювання затухаючих коливань для кожного зразка; Визначити коефіцієнт демпфування та відсоток гасіння вібрації; провести обробку експериментальних даних з метою виявлення оптимальних комбінацій матеріалу і геометричних параметрів; виявлено закономірність впливу жорсткості матеріалу, перфорації та патерну отворів на демпфувальні властивості лайнерів. **Результати**: реалізовано та експериментально перевірено метод оцінки демпфувальних характеристик 3D-друкованих TPU-лайнерів із керованою внутрішньою структурою. Встановлено нелінійну залежність ефективності гасіння вібрацій від ступеня перфорації та систематичне зменшення демпфування зі зростанням жорсткості TPU. Показано, що шестикутна геометрія отворів забезпечує більш рівномірний розподіл деформацій і дещо вищу ефективність гасіння порівняно з ромбічною та трикутною. Отримані залежності дозволяють цілеспрямовано проєктувати демпфувальні лайнери з оптимальним співвідношенням жорсткості та здатністю до гасіння вібрації. Це дозволить вирішити наступні питання, такі як: зниження ударних навантажень – зменшення пікових динамічних сил, що передаються від гільзи протеза до м'яких тканин кукси; перерозподіл тиску – формування більш рівномірних контактних напружень у зоні контакту виробу зі шкірою; підвищення комфорту користувача – зменшення вібрацій, болю та подразнення шкіри під час ходьби; індивідуальна оптимізація – персоналізований підбір геометрії та матеріалу лайнеру під параметри тіла, рівня активності та стану тканин пацієнта; інженерне проектування – створення структурно оптимізованих елементів для біомединого застосування. **Висновки**: за результатами роботи експериментально підтверджено можливість керування демпфувальними властивостями TPU-лайнерів шляхом зміни жорсткості матеріалу, ступеня перфорації та геометрії отворів. Встановлено наявність оптимального діапазону перфорації для кожного рівня жорсткості TPU, а також переваги шестикутної перфорації з точки зору рівномірності деформацій та ефективності гасіння вібрацій.

Ключові слова: TPU-лайнери; 3D-друк; жорсткість матеріалу; протези; ударні випробування.

Бібліографічні описи / Bibliographic descriptions

Невлюдов І. Ш., Рубан О. А., Нікітін Д. О., Місан Б. С., Іохов О. Ю. Дослідження демпфувальних властивостей 3D-друкованих лайнерів з керованою перфорацією. *Сучасний стан наукових досліджень та технологій в промисловості*. 2026. № 1 (35). С. 154–167. DOI: https://doi.org/10.30837/2522-9818.2026.1.154

Nevlyudov, I., Ruban, O., Nikitin, D., Misan, B., Iokhov, O. (2026), "Investigation of the damping properties of 3D-printed liners with controlled perforation", *Innovative Technologies and Scientific Solutions for Industries*, No. 1 (35), P. 154–167. DOI: https://doi.org/10.30837/2522-9818.2026.1.154