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Numerical Modal Analysis of a Multi-Material 3D-Printed Composite Bushing and Its Application

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***Abstract*—**Modal analysis is a crucial tool in the field of engineering for understanding the dynamic behavior of structures. In this study, numerical modal analysis was conducted on a multi-material 3D-printed composite bushing, which comprised a polylactic acid (PLA) outer shell and a thermoplastic polyurethane (TPU) flexible filling. The objective was to investigate the modal characteristics of the bushing and assess its potential for practical applications. The analysis involved the development of a finite element model of the bushing, which was subsequently subjected to modal analysis techniques. Natural frequencies, mode shapes, and damping ratios were determined to identify the dominant vibration modes and their corresponding responses. The numerical modal analysis provided valuable insights into the dynamic behavior of the bushing, enabling a comprehensive understanding of its structural integrity and performance. Furthermore, the study expanded its scope by investigating the entire shaft mounting of a small electric car, incorporating the 3D-printed composite bushing. The shaft mounting system was subjected to numerical modal analysis to evaluate its dynamic characteristics and potential vibrational issues. The results of the modal analysis highlighted the effectiveness of the 3D-printed composite bushing in minimizing vibrations and optimizing the performance of the shaft mounting system. The findings contribute to the broader field of composite material applications in automotive engineering and provide valuable insights for the design and optimization of similar components.

***Keywords*—**3D printing, composite bushing, modal analysis, multi-material.

I. Introduction

MODAL analysis is a fundamental and indispensable tool in the field of engineering for comprehending the dynamic behavior of structures. It allows engineers to study the natural frequencies, mode shapes, and damping ratios of a system, which are essential in understanding its vibrational response and structural integrity. In this study, we focus on the numerical modal analysis of a multi-material 3D-printed composite bushing, designed for potential application in the automotive industry.

The composite bushing under investigation is composed of two distinct materials: a PLA outer shell and a TPU flexible filling. This unique combination of materials offers the possibility of achieving a desirable balance between stiffness and flexibility, making it an attractive candidate for various mechanical applications. The objective of this research is to explore the modal characteristics of the 3D-printed composite bushing and evaluate its suitability for practical engineering purposes [1], [2]. To achieve this goal, we developed a finite element model of the composite bushing, which was subsequently subjected to numerical modal analysis techniques. By utilizing finite element methods, we were able to simulate the dynamic behavior of the bushing and extract vital modal parameters, such as natural frequencies, mode shapes, and damping ratios. These parameters enable us to identify the dominant vibration modes and their corresponding responses, crucial for assessing the effectiveness and performance of the composite bushing.

The outcomes of the numerical modal analysis provide valuable insights into the dynamic behavior of the multi-material 3D-printed composite bushing. These insights not only contribute to a comprehensive understanding of the bushing's structural integrity but also offer valuable information for optimizing its performance in practical applications. The investigation also goes beyond the individual component and delves into a broader application context by studying the entire shaft mounting of a small electric car, incorporating the 3D-printed composite bushing [1]-[3].

By subjecting the shaft mounting system to numerical modal analysis, we aimed to evaluate its dynamic characteristics and identify any potential vibrational issues [4]. The successful integration of the 3D-printed composite bushing into the shaft mounting system is expected to mitigate vibrations and enhance the overall performance of the system, which is crucial in the automotive industry, where ride comfort and safety are significant concerns.

The results of the modal analysis shed light on the effectiveness of the multi-material 3D-printed composite bushing in reducing vibrations and optimizing the performance of the shaft mounting system [4], [5]. The positive findings from this study not only validate the use of composite materials in automotive engineering but also provide valuable insights for the design and optimization of similar components. As 3D-printing technology continues to advance, the practical applications of composite materials in various engineering fields are likely to expand, making this research relevant and significant for current and future engineering endeavors [6]-[8].

In summary, this paper presents a comprehensive investigation of the numerical modal analysis of a multi-material 3D-printed composite bushing. By exploring its modal characteristics and its integration into a shaft mounting system, this study aims to advance the understanding of composite materials' potential in engineering applications. The findings

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contribute to the broader field of composite material applications in automotive engineering, with implications for enhancing ride comfort and safety in vehicles. The knowledge gained from this research can guide the design and optimization of similar components, showcasing the promising future of composite materials and 3D-printing technology in engineering disciplines.

II. Material and Methods

This chapter presents the applied methodology for conducting numerical modal analysis on the multi-material 3D-printed composite bushing. This chapter outlines the materials and process used in fabricating the composite bushing, including the PLA outer shell and the TPU flexible filling. The 3D-printing process and specific parameters employed for the fabrication of the bushing are detailed, ensuring reproducibility and consistency in the experimental setup.

Additionally, steps involved in performing the modal analysis, such as the identification of natural frequencies, mode shapes, and damping ratios, are described in a systematic manner. Furthermore, the integration of the 3D-printed composite bushing into the shaft mounting system of a small electric car is elaborated upon, including the numerical modeling of the entire system.

A. 3D Printing of the PLA-TPU Bushing

First step of the research was preparing the geometry and 3D-printing the PLA-TPU bushing. The part consisted of PLA outer shells with TPU rubber, elastic filling. Selection method of 3D printing was FDM (Fused Deposition Modelling) utilizing Prusa MK3 printer with multi material extension [2].

B. Modal Analysis of the Bushing

The main phase of this research was the modal analysis of the designed suspension elements. Although sufficient studies have been published in the field of modal analysis application, no studies have been found on modal analysis application in FDM of multi material prints [9]-[11].

Modal analysis and random vibration analysis were performed in ANSYS 19.2. Academic software. The modal analysis was carried out for two different geometries - a simple suspension bushing model and the bushing together with a shaft mounting. Both geometries are presented in Fig. 1.

The first stage was modal analysis of a simple bushing. In total, four models have been compared. Among tested models were three models of the FDM printed PLA-TPU bushing and one model of a simple steel bushing, which is still applied today in the Silesian Greenpower vehicle [12]-[15]. The CAD models of the FDM printed bushing represented two different materials: the 1 mm outer layers of PLA and a TPU rubber filling. Different types of TPU fillings have been chosen: a full filling and a V-shaped pattern with two different thicknesses. The V-shaped filling pattern has been specifically designed to reduce the needed material and printing time, while providing optimal mechanical properties. Two variants of the V-shape infill pattern have been inspected, 1 mm thick and 2 mm thick.

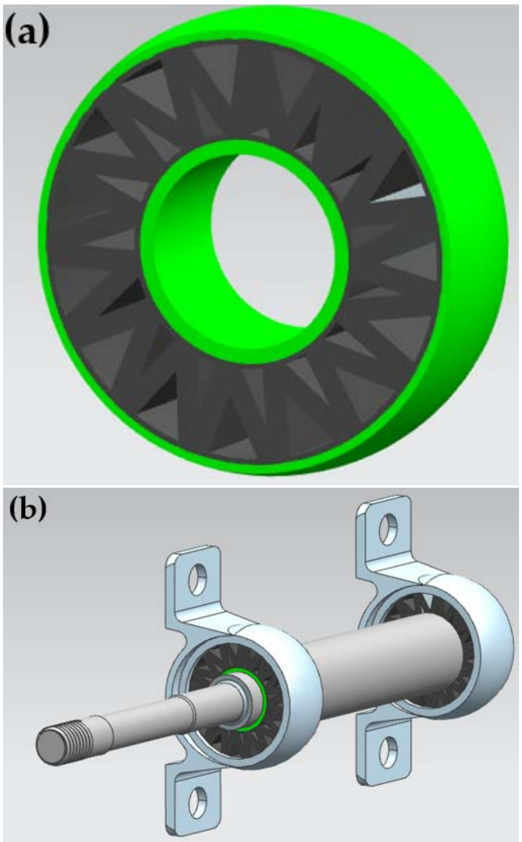

Fig. 1 Geometries of the analyzed models: simple bushing (a) and whole shaft mounting (b)

The whole shaft model consisted of three types of elements: the shaft, bushings, and mounting frames. The material assigned to the shaft and mounting frames was structural steel. The bushings materials have been set accordingly to each of four different models [16].

Modal analysis and random vibration analysis have been carried out in the ANSYS Mechanical 19.2. Academic software. Appropriate materials have been set for each model: PLA and TPU for dual material 3D printed bushings and structural steel for metal one. As a boundary condition, the bushing was fixed on the inner surface, which represented the mounting on a shaft [17]-[21].

As a result of the modal analysis, six own frequencies of each model have been obtained. These values were further applied as input data for random vibration analysis. Random vibration analysis was performed using a PSD G acceleration model. PSD stands for power spectral density of a signal. The parameters of this solution model are presented in Table I. Random vibration analysis allowed us to calculate the probability of directional deformation and stress 3σ probability, which is 99,7%.

C. Modal Analysis of the Shaft with a Bushing

The same procedures and analyzes were carried out for four models of shaft mounting with a bushing suspension: three FDM printed models and with a steel bushing. The main difference was that 18 own frequencies were determined. This was due to the larger number of degrees of freedom of the system analyzed.

TABLE I
PARAMETERS OF THE PSD G ACCELERATION SOLUTION MODEL

Frequency [Hz]	G Acceleration [G^2/Hz]
10	0,1
100	0,5
1000	0,5
2000	0,2

III. RESULTS AND DISCUSSION

A. Modal Analysis

As a result of the numerical modal analysis carried out in the ANSYS software, five own frequencies for each simple bushing model have been obtained. The results acquired for each bushing model are presented in Table II.

TABLE II
OWN FREQUENCIES OF EACH BUSHING MODEL

No.	Frequency [Hz]			
	PLA-TPU 1 mm	PLA-TPU 2 mm	PLA-TPU full	Steel
1.	0,9750	1,8192	2,7665	39334
2.	1,6475	2,2507	3,0054	42723
3.	1,6482	2,2509	3,0054	42723
4.	2,0789	2,7901	3,6933	44330
5.	3,0000	4,3300	6,2192	47895

The own frequencies for the composite bushings varied between 0,975 Hz and 6,2192 Hz, whereas for the steel bushing between 39334 Hz and 47895 Hz. It can be seen that as the PLA-TPU bushing filling increases, the individual natural frequencies in-crease successively. Disregarding the first frequency, the others increase by about 30-40% with increasing filling density, respectively.

Based on the results of the modal analysis, possible maximal deformations and stresses have been calculated in the random vibration analysis. The random vibration results are presented in Table III.

TABLE III
DIRECTIONAL DEFORMATION AND STRESS FOR EACH BUSHING MODEL

	Deformation X [mm]	Deformation Y,Z [mm]	Stress von Mises [MPa]
PLA-TPU 1 mm	1,32	5,22	2,01E-04
PLA-TPU 2 mm	1,47	5,55	3,06E-04
PLA-TPU full	1,02	5,32	2,66E-04
Steel	2,66E-10	9,81E-11	7,37E-06

The X direction was the axial directions; therefore, the Y and Z direction were identical considering the cylindrical shape of the bushing. Deformation and von Mises stress were calculated for 3σ probability which is 99,7%. To elaborate, the 3σ deformation means that for 99,7% the deformation will not exceed the given value. The de-formation values for steel bushings are negligible. The directional deformations in the X and Y direction for composite bushing with a filling of 2 mm thick are presented in Figs. 2 (a) and (b). The deformation in the X direction for the composite bushing with 2 mm thick filling was 11,36% higher than for the 1 mm thick filling. The deformation in the X di-rection for the full PLA-TPU bushing was 44,12% smaller than for the 2 mm thick infill. The deformation in the Y direction for the composite bushing with 2 mm thick filling was 6,32% higher than for the 1 mm thick filling and 4,32% higher than for the full TPU filling. The calculated von Mises stresses for all models are negligible.

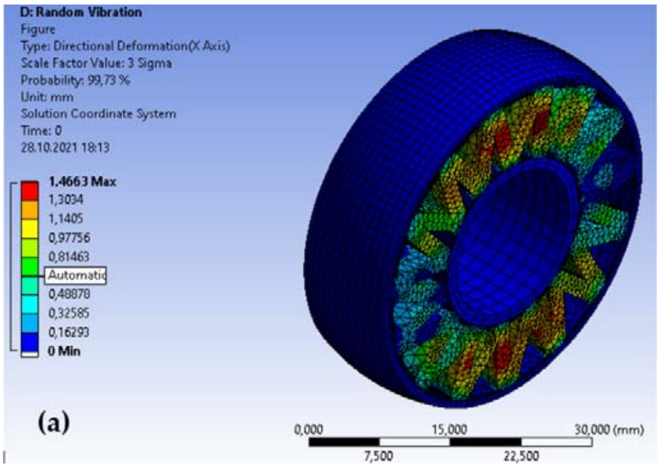

Fig. 2 (a) Deformation in X direction - axial

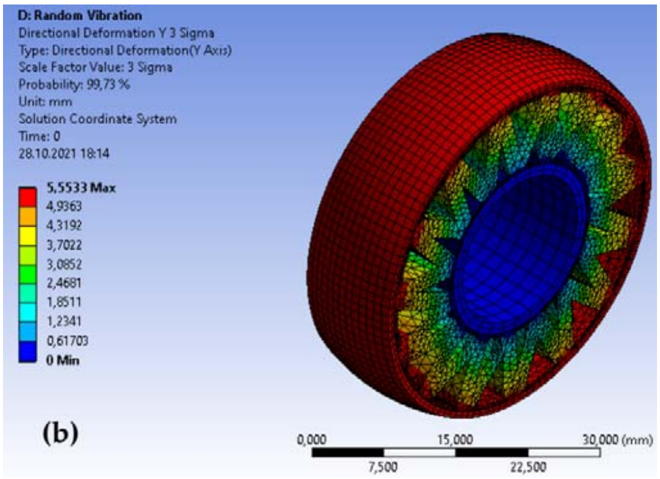

Fig. 2 (b) Deformation in Y direction

Fig. 2 Comparison of the directional deformations for bushing with 2 mm thick V-shape filling

The next step was to establish their own frequencies, directional deformations, and stresses for the whole shaft mounting with different bushings. The model of the shaft consisted of three types of elements, the shaft, bushings, and mounting frames. The results of the modal analysis of the whole shaft are presented in Table IV.

The spectrum of its own frequencies for shafts with V-shaped bushings filling varied between 0,23246 Hz and 152,34 Hz. Analogously to the results for the sleeve itself, the eigenfrequencies increase correspondingly with increasing filling of the PLA-TPU composite sleeves. Apart from the first few own frequencies, the others increase by more than 50%, respectively, with increasing fill density. The spectrum of own frequencies for shaft with steel bushings varied between 822,99 Hz up to 13971 Hz. Based on the results of the modal analysis, possible maximal deformations and stresses have been calculated in the random vibration analysis. The random vibration results are presented in Table V. In this case, the directional deformations have been calculated in all three directions. The Z direction was the axial direction of the shaft. The deformation in the X di-rection decreases approximately twofold as the fill density of the 3D printed composite bushings increases.

TABLE IV
OWN FREQUENCIES OF EACH SHAFT MODEL

No.	Frequency [Hz]			
	PLA-TPU 1 mm	PLA-TPU 2 mm	PLA-TPU full	Steel
1.	0,23246	0,3076	0,4421	822,99
2.	0,31875	0,4582	0,6974	828,19
3.	0,31925	0,4587	0,6987	3026,5
4.	19,905	20,273	20,03	3875,1
5.	21,244	21,652	21,173	4335,9
6.	79,863	122,88	121,3	4343,5
7.	83,28	137,24	216,54	4431,0
8.	85,087	138,28	217,07	5777,5
9.	85,521	139,34	217,76	6578,7
10.	85,724	139,34	217,86	6707,6
11.	85,783	140,18	218,78	7476,5
12.	85,889	140,86	219	8215,2
13.	86,717	144,21	220,82	9172,4
14.	87,052	144,29	221,14	9676,4
15.	87,245	144,70	225,75	11482
16.	87,359	145,89	225,84	11956
17.	88,061	151,00	226,82	12062
18.	88,277	152,34	226,93	13971

TABLE V
DIRECTIONAL DEFORMATION AND STRESS FOR EACH SHAFT MODEL

	Deformation X [mm]	Deformation Y [mm]	Deformation Z [mm]	Stress von Mises [MPa]
PLA-TPU 1 mm	4,03	1,42	5,51	2,60E-01
PLA-TPU 2 mm	2,06	1,42	5,52	2,00E-01
PLA-TPU full	1,10	2,36	5,08	5,82E-01
Steel	2,15E-02	6,48E-02	2,97E-01	1,21E+02

The directional deformations for both shafts with dual material bushings with V-shaped filling are the same in the Y direction – 1,42 mm. The Y deformation of the composite bushing with full TPU filing is 66,2% higher than for other PLA-TPU bushings. The difference in the deformation values in the Z direction is less than 9%. The axial deformation of the shaft with the composite bushing with 2 mm thick V-shaped filling is presented in Fig. 3.

Again, directional deformations for the shaft with the steel bushing are negligible. Also, the calculated von Mises stresses for all three models with PLA-TPU bushings are negligible. The stresses for the steel bushing shaft model are much higher than for the composite bushing models and were 121 MPa, which is not a dangerous value given the presence of only steel system components.

IV. CONCLUSIONS

Modal and random vibration analysis was performed for four bushing models, as well as the entire shaft mount including the bushings. A comparative analysis was performed for newly designed bushings made of two materials (PLA composite with TPU filling) made as 3D prints in FDM technology with the full steel bushing currently used in the car. Modal analysis was used to determine the natural frequencies of both the bushings themselves and the shaft mount.

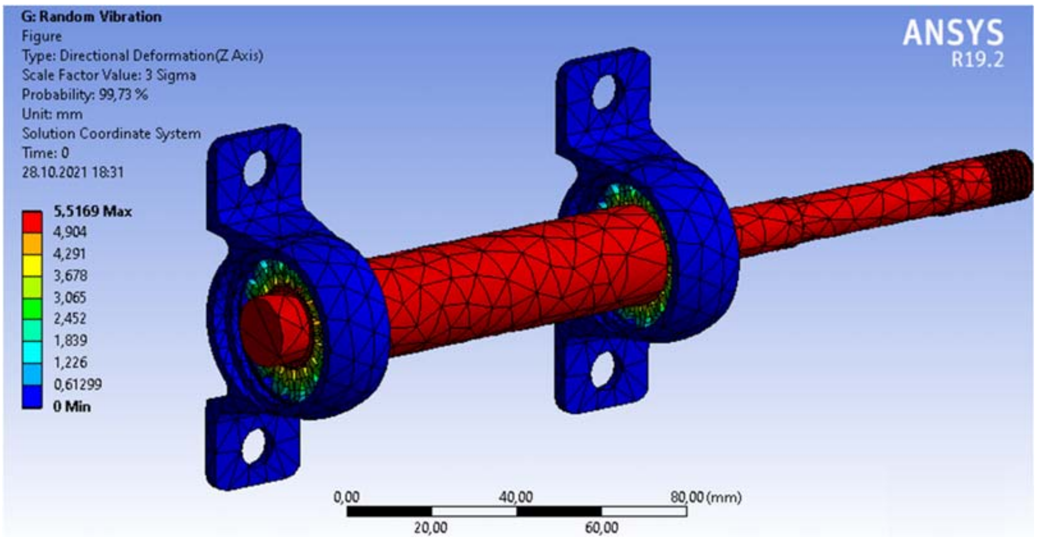

Fig. 3 The axial deformation of the shaft model with PLA-TPU bushing with 2 mm thick V-shaped filling

In summary, the modal analysis conducted via ANSYS revealed distinct trends in the natural frequencies of the studied bushing and shaft systems. Increasing PLA-TPU composite bushing filling correlated with higher eigenfrequencies, while the steel bushing demonstrated a notably elevated frequency range. Random vibration analysis indicated that higher composite bushing filling densities led to proportional directional deformations, particularly in the X and Y directions. The entire shaft assembly analysis reinforced these trends, with eigenfrequencies increasing with higher PLA-TPU composite bushing fillings. The comprehensive study informs the optimization of 3D printed composite bushing designs, emphasizing their enhanced performance and reliability across diverse engineering applications.

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