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PREFACE

Modern product development is no longer just an engineering process – it is a strategic activity that connects technology, the market, design, user experience, and sustainability. Market success depends on the ability to develop innovative solutions quickly, efficiently, and intelligently, using the latest technologies. For this reason, product development must be at the core of educational programs, research centers, and industrial strategies. Today's technological trends – including artificial intelligence, additive manufacturing methods, digitalization, and environmentally sustainable industry – open up a broad range of new perspectives and opportunities for the advancement of this dynamic profession.

The 11th International Scientific Conference – IRMES 2025 – Research and Development of Mechanical Elements and Systems is organized by the Chair of Mechanical Constructions, Development, and Engineering at the Faculty of Mechanical Engineering, University of Niš, and the Association for Design, Elements and Constructions – ADEKO. With a tradition of over three decades, IRMES remains committed to its mission – to bring together researchers, engineers, industry representatives, and students with the aim of enhancing knowledge and its application in industry.

At the previous ten IRMES conferences (the first held in 1995), around one thousand papers were presented, with participation from over one thousand individuals from across the globe. This long-standing and successful tradition forms a solid foundation for organizing this and future IRMES conferences.

All submitted papers for IRMES 2025 underwent international peer review, and 37 papers met the high standards required for publication in the Conference Proceedings. The accepted papers are categorized into four thematic areas of the conference: Mechanical Elements and Systems, Product Development Process, Advanced Technologies in Mechanical Engineering and Mechanical Engineering Education.

We are especially pleased that a significant number of participants from abroad have registered for IRMES 2025. In total, 119 authors from 11 countries are participating. During the two plenary sessions, lectures will be delivered by distinguished professors:

- Prof. Dr.-Ing. Dr. h.c. Bernd-Robert Höhn, Technical University of Munich, School of Engineering and Design
- Prof. Dr. Dražan Kozak, University of Slavonski Brod, Faculty of Mechanical Engineering
- Prof. Dr. Damjan Klobčar, University of Ljubljana, Faculty of Mechanical Engineering
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- Prof. Dr. Vladimir Milovanović, University of Kragujevac, Faculty of Engineering
- Prof. Dr. Milan Banić, University of Niš, Faculty of Mechanical Engineering

In today's rapidly changing world, influenced by global economic, environmental, and social factors, it is essential that all of us involved in mechanical engineering in various capacities remain aware of our responsibility. In this context, engineering ethics, quality of work, and lifelong learning play a vital role. Although scientific research is fundamental to economic progress, the education of new generations of mechanical engineers is equally important.

As part of the conference, a Panel Session will be held under the title: The Future of Mechanical Engineering Education: Mechanical Engineering in the Era of Artificial Intelligence.

We are confident that the work at IRMES 2025 will be fruitful and that each of you will leave the conference with new ideas, knowledge, and contacts that will support your further professional development. This is an opportunity not only to learn from one another but also to jointly build the foundation for future research projects and industrial innovations.

Moreover, we hope that in the coming days, we will have the opportunity to get to know each other better, discuss common challenges, and establish new forms of collaboration. In this sense, we emphasize that all your suggestions and proposals are more than welcome and will be carefully considered by the Organizing and Scientific Committees with the aim of improving future conferences.

IRMES 2025 will be further enriched by additional events to support the effective exchange of knowledge and experiences, as well as to ensure a pleasant stay in Vrnjačka Banja in June 2025.

We would like to thank all authors, committee members, reviewers, and others who contributed to the organization and relevance of this conference. Without their support, the organization and realization of IRMES would not have reached the level that its importance and reputation deserve. Special appreciation goes to the Ministry of Science, Technological Development and Innovation and to our general sponsor DB-RAZVITAK d.o.o. Veternik, whose support was crucial.

We wish all participants a successful IRMES 2025 and a pleasant stay in Vrnjačka Banja.

Niš, June 12th, 2025

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11th International Scientific Conference

IRMES 2025

Research and Development of Mechanical Elements and Systems

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ANALYSIS OF NATURAL FREQUENCIES OF A HYBRID ALUMINUM/COMPOSITE SHAFT

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Abstract: *The study analyzes the influence of material type, shaft wall thickness, and fiber orientation angle on the natural frequencies of a hybrid aluminum/composite driveshaft for a Nissan vehicle. The composite layers were made of carbon, glass, and aramid fibers combined with epoxy resin. The analysis was conducted using the Finite Element Method (FEM) within the FEMAP 2021.2 software package. The results showed that reducing the shaft wall thickness leads to an increase in the natural frequency values. It was also concluded that hybrid shafts combining aluminum and carbon fiber/epoxy composites exhibit the highest natural frequencies, while increasing the fiber orientation angle in the layers reduces the natural frequency values for all analyzed material types.*

Keywords: *aluminum/composite driveshaft; carbon fibers; glass fibers; aramid fibers; natural frequencies.*

1. INTRODUCTION

The role of an automobile driveshaft is to transmit power, i.e., torque, from the engine to the differential gears and further to the vehicle's wheels. A specific characteristic of these shafts is the transmission of torque at varying angles between transmission components.
To achieve satisfactory natural frequency values, steel driveshafts are most commonly manufactured as two-piece assemblies connected by joints. Synchronization between shaft joints is achieved using universal (Cardan) joints, which allow angular misalignment by enabling rotation around two axes.
In order to ensure effective power transmission, a driveshaft must meet three basic requirements:

- the ability to operate at high rotational speeds, i.e., to achieve high natural frequencies,
- sufficient load-carrying capacity, i.e., the ability to transmit the required torque,
- adequate torsional flexibility.

Metal driveshafts have certain limitations, primarily due to their high mass and the inability to reach high critical speeds, i.e., rotational speeds. To reduce their weight, such shafts are typically manufactured as hollow; however, it is necessary to account for the allowable values of torsional deformation.
Given the growing emphasis on environmental protection, there is a strong motivation to reduce vehicle weight by decreasing the mass of individual components, including the driveshaft. This would directly contribute to reduced fuel consumption and lower emissions of harmful gases, thereby improving overall quality of life.
One effective approach to weight reduction is the use of composite materials—such as carbon, glass, or aramid fibers combined with suitable resins—in driveshaft manufacturing. Composite materials exhibit high specific strength (R_m/ρ) and specific modulus (E/ρ). These material properties allow the shafts to transmit the required torque, reach appropriate rotational speeds, resist corrosion and fatigue, reduce noise and vibration, and achieve a long service life, among other benefits.
In the study [1], the authors analyzed the influence of the number of layers and fiber orientation in the layers of a composite driveshaft, taking into account specific design and reliability constraints. Among other findings, it was concluded that a drive shaft made of carbon fiber reinforced plastic (CFRP) has a 30% lower mass compared to an equivalent metal shaft, while maintaining satisfactory reliability.

Study [2] focuses on the dynamic behavior of carbon/epoxy and boron/epoxy composite shafts with a mounted disk. The influence of the disk position along the shaft, as well as the fiber orientation angle in the composite, on the critical speed and natural frequencies of the shaft was analyzed.
In study [3], the authors investigated the effect of the length-to-mean-diameter ratio of carbon/epoxy, glass/epoxy, and boron/epoxy shafts on the natural frequency values. Additionally, the influence of fiber orientation angle on this characteristic was considered.
The main objective of study [4] was to explore the feasibility of manufacturing driveshafts from more environmentally friendly materials. In addition to different materials (natural fibers, synthetic fibers, and hybrid natural/synthetic fibers combined with epoxy resin), the effects of fiber orientation and laminate stacking sequence on stress levels and natural frequencies were also examined.
In study [5], the authors investigated whether natural fibers can adequately replace synthetic fibers in driveshaft manufacturing. They analyzed both solid and hollow shafts made of kenaf fibers, as well as hybrid shafts combining glass and kenaf fibers. It was concluded that hybrid shafts exhibit significantly better performance characteristics, and that, when using composite materials, it is crucial to align the reinforcing fibers in the direction of the applied load.
In study [6], the authors explored the potential of replacing conventional steel driveshafts with composite shafts made from basalt/epoxy, carbon/epoxy, and carbon nanotube (CNT) reinforced carbon/epoxy composites. The results indicated that the use of composite materials can lead to weight savings of up to 90%, while achieving safety factors up to 50% higher.

2. CHARACTERISTICS OF THE COMPOSITE DRIVESHAFT

Testing has shown that switching from a steel to a composite driveshaft results in an approximate 5% increase in wheel power due to reduced mass. Composite fibers (such as carbon, glass, etc.) help reduce vibrations, thereby minimizing power losses. Specifically, the composite driveshaft absorbs part of the impact loading, which reduces the load on the entire drivetrain and enables a more uniform stress distribution, positively affecting the service life of the entire system.
The analyzed driveshaft corresponds to a 2004 Nissan 350Z vehicle (Figure 1).

Fig.1. Nissan 350Z driveshaft [7]

The aim of the study was to analyze the natural frequency values of hybrid driveshafts made by combining aluminum with carbon, glass, and aramid fibers in epoxy resin. Specifically, eight composite layers, each 0.12 mm thick, were applied around the aluminum tube using the mentioned materials. The study analyzed the influence of fiber type, fiber orientation angles in the layers, and the wall thickness of the hollow driveshaft on the natural frequency values, i.e., the critical speed of the driveshaft.
The characteristics of the analyzed driveshaft materials are presented in Table 1.

Table 1. Material Properties of the Driveshaft

Material	Elasticity modulus E_1, MPa	Elasticity modulus E_2, MPa	Density ρ, kg/m^3
Aluminum	72000	72000	2695
USN 150 carbon /epoxy	131600	8200	1550
UGN 150 glass/epoxy	43300	14700	2100
UKN 100 aramid/epoxy	81800	5100	1380

The length of the analyzed driveshaft is 1500 mm, and the mean diameter is 78 mm.

3. ANALYSIS OF THE DRIVESHAFT'S NATURAL FREQUENCIES

The natural frequency of the driveshaft is the frequency at which the shaft naturally vibrates or oscillates under the influence of an applied load, i.e., it represents the structure's response to dynamic excitation. The values of the natural frequencies depend on the shaft's geometric dimensions, mass, and material.
Natural frequencies are an important parameter in the analysis and design of all mechanical systems. Knowing the natural frequency values can prevent the occurrence of unwanted vibrations that lead to material fatigue, structural damage, and reduced service life.
The analysis of the natural frequencies was performed using the Finite Element Method (FEM) in the FEMAP 2021.2 software. The model of the analyzed driveshaft, along with the generated finite element mesh, is shown in Figure 2.

Fig.2. Driveshaft finite element model

The influence of the material type (aluminum, Al/USN 150 carbon/epoxy, Al/UGN 150 glass/epoxy, and Al/UKN 100 aramid/epoxy), wall thickness of the shaft with a ring cross-section (1.5 mm, 2 mm, 2.5 mm, and 3 mm), and the fiber orientation angle in the laminate layers (0°, ±15°, ±30°, ±45°) on the natural frequency values of the driveshaft was analyzed. The obtained natural frequency values for a fiber orientation angle of 0° in all laminate layers are shown in the form of a diagram in Figure 3.

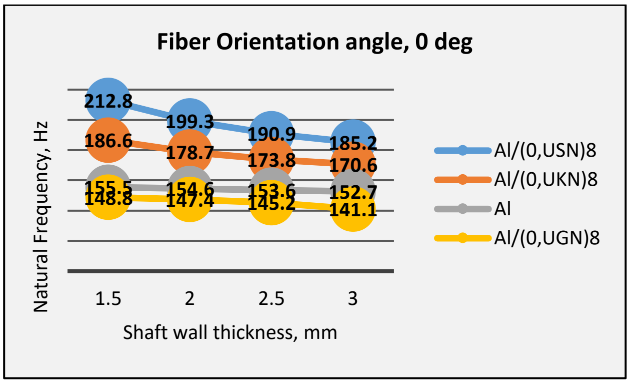

Fig.3. Natural frequencies of the driveshaft at a fiber orientation angle of 0°

Analysis of Figure 3 shows that the best performance is exhibited by the hybrid driveshaft composed of aluminum and carbon fiber/epoxy composite (Al/[0_{USN}]$_8$). Slightly lower performance is observed when carbon fibers are replaced with aramid fibers (Al/[0_{UKN}]$_8$), while the combination of aluminum and glass fiber/epoxy composite (Al/[0_{UGN}]$_8$) yields the lowest performance. Regarding the shaft wall thickness, it is observed that an increase in thickness leads to a decrease in the natural frequency values. This effect is particularly pronounced in the case of carbon and aramid fibers. Specifically, for carbon fibers, increasing the wall thickness from 1.5 mm to 3 mm results in a reduction of natural frequencies by approximately 13%, while for aramid fibers the reduction is about 9%. The influence of wall thickness is less significant in the case of glass fibers, with a decrease of around 5%. For the pure aluminum shaft, the wall thickness of the aluminum tube has a minimal effect, where increasing the thickness from 1.5 mm to 3 mm leads to a reduction in natural frequencies of only about 2%.

The relationship between the natural frequencies and the wall thickness of the driveshaft for the same materials, but with a fiber orientation of ±15° in the laminate layers, is shown in Figure 4.

It can be concluded that, similar to the case with 0° fiber orientation, the best results are achieved with the Al/[$\pm15_{USN}$]$_4$ material configuration. However, the natural frequency values are lower compared to the previous orientation (0°). The same trend is observed for the other materials as well.

For this fiber orientation as well, the lowest natural frequency values are obtained with the aluminum/glass fiber/epoxy composite material (Al/[$\pm15_{UGN}$]$_4$). As in the case of 0° fiber orientation, the natural frequency values for this material are lower than those of the pure aluminum driveshaft.

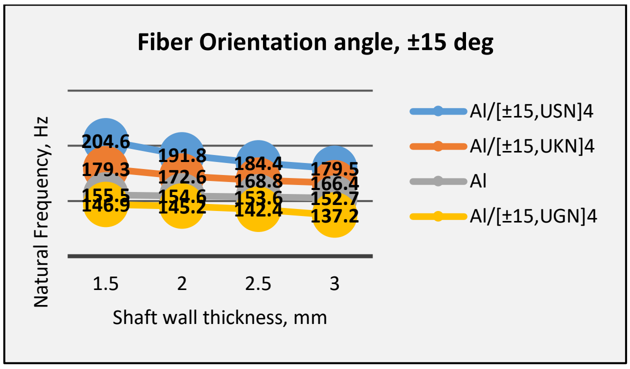

Fig.4. Natural frequencies of the driveshaft at a fiber orientation angle of ±15°

The same analysis was carried out for the case of fiber orientation angles of ±30° (Figure 5), as well as for fiber orientation angles of ±45° (Figure 6).

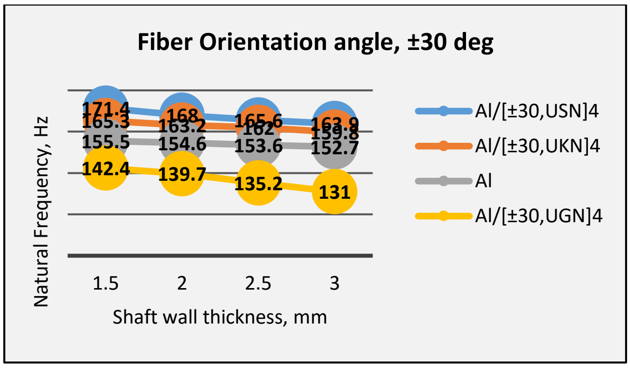

Fig.5. Natural frequencies of the driveshaft at a fiber orientation angle of ±30°

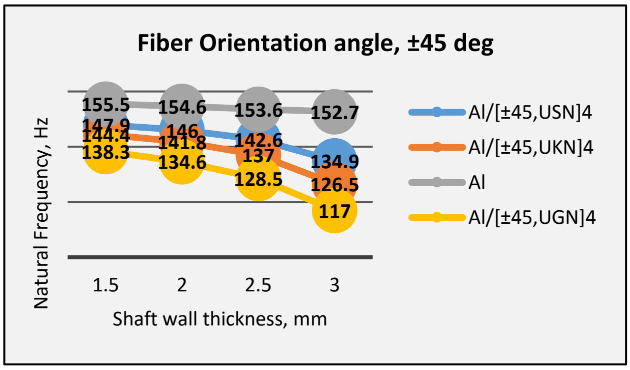

Fig.6. Natural frequencies of the driveshaft at a fiber orientation angle of ±45°

By analyzing the natural frequency values shown in Figures 3, 4, 5, and 6, it can be concluded that for fiber orientation angles of 0°, ±15°, and ±30°, the best results are achieved with the aluminum/carbon fiber/epoxy composite material (Al/USN), followed by the aluminum/aramid fiber/epoxy composite (Al/UKN), while the aluminum/glass fiber/epoxy composite (Al/UGN) shows the lowest natural frequency values. It can also be concluded that increasing the fiber orientation angle leads to a decrease in the natural frequency values, and this trend holds for all materials used. In the case of ±45° fiber orientation, the natural frequencies of all hybrid driveshafts are lower than those of the pure aluminum shaft.

The significant influence of fiber orientation on the natural frequencies is evident in the case of the highest-performing composite material (carbon fiber/epoxy), where increasing the fiber orientation angle from 0° to ±45° results in a reduction of the driveshaft's natural frequency values by approximately 27%.

It can also be concluded that the wall thickness of the driveshaft has a significant influence on the values of natural frequencies. For all materials and all fiber orientation angles, an increase in wall thickness results in a decrease in natural frequency values.

It is well known that the mass of the shaft, i.e., the ratio E/ρ, has a major impact on natural frequency values. Given that the carbon fiber/epoxy composite has the highest value of this ratio, it is clear why the highest natural frequencies are achieved with this material. On the other hand, the glass fiber/epoxy composite is characterized by the lowest E/ρ ratio among all the analyzed materials, which explains its correspondingly lower natural frequency values.

The natural frequency in the first mode of vibration f_i and the circular (angular) frequency ω_i are related by the following expression:

$$f_i = \frac{\omega_i}{2\pi}, Hz \tag{1}$$

so that the critical rotational speeds can be easily determined using the following expression:

$$f_i = 60 \cdot n_i, \min^{-1} \tag{2}$$

where fi, Hz are the values of the natural frequencies.

It is evident that the highest critical rotational speeds are achieved using carbon fiber/epoxy composites, followed by the aramid fiber/epoxy combination, while the glass fiber/epoxy combination results in the lowest critical speeds.

4. CONCLUSION

The rapid advancement of technology requires the use of new composite materials that improve product performance, reduce weight, and offer significant flexibility in terms of design and shaping. By reducing the mass of an automotive composite driveshaft, the energy required to start the vehicle—as well as fuel consumption—is significantly decreased. From an environmental standpoint, this is highly important, as it also leads to reduced pollution.

In this study, the natural frequencies of hybrid driveshafts for the Nissan 350Z were analyzed. These shafts were manufactured by combining aluminum with carbon (Al/CF), glass (Al/GF), and aramid (Al/AF) fibers in conjunction with epoxy resin. The analysis was performed using the finite element method (FEM), and the following conclusions were drawn:

- The material of the shaft significantly affects the natural frequencies. The highest values are achieved using the Al/USN material, while the combination of aluminum with glass fibers (Al/UGN) gives the poorest results,
- Increasing the wall thickness of the hollow shaft reduces the natural frequency values for all shaft materials,
- The fiber orientation angle in the composite layers has a significant impact on the natural frequencies. The smaller the fiber orientation angle, the higher the natural frequencies. An increase in the fiber orientation angle from 0° to ±45° can lead to a reduction in the natural frequency values by nearly 30%,
- The mass of the shaft greatly influences the natural frequencies, which is why the best results are achieved with the combination of aluminum and carbon fibers.

To prevent resonance, i.e., the coincidence of the actual and critical rotational speed, for metallic shafts, it is necessary to make some geometric changes to the shaft or change the material. This study has shown that, in the case of composite materials, this can be achieved only by changing the fiber orientation angle in the laminate layers.

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