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SELECTION OF SHAFT MATERIALS USING A MULTICRITERIA APPROACH

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RESEARCH ARTICLE

ABSTRACT: The aspiration of modern mechanisms is to achieve the highest possible speed of work. The same requirements apply to transmission shafts, so a precise dynamic analysis of the stability of these elements is very important. It is known that the frequency of oscillation is directly proportional to the elasticity of the body, and inversely proportional to the mass of the body. The essence of the work is in the selection of the optimal shaft material in order to avoid the occurrence of resonance that can lead to different types of shaft destruction. Aluminum and composite carbon fiber shafts in combination with epoxy resin were analyzed. The paper proposes a multicriteria approach (MCDM) for the selection of the optimal transmission shaft material. It is emphasized how suitable this method is for analyzes of this type because it includes the influence of numerous qualitative and quantitative properties of materials in the selection.

KEY WORDS: *multi-criteria decision making, shaft, material, composite*

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IZBOR MATERIJALA VRATILA VIŠEKRITERIJUMSKIM PRISTUPOM

REZIME: Težnja savremenih mehanizama je postizanje najveće moguće brzine rada. Isti zahtevi važe i za prenosna vratila, pa je precizna dinamička analiza stabilnosti ovih elemenata veoma važna. Poznato je da je frekvencija oscilovanja direktno proporcionalna elastičnosti tela, a obrnuto proporcionalna masi tela. Cilj rada je izbor optimalnog materijala vratila kako bi se izbegla pojava rezonancije koja može dovesti do različitih oštećenja osovine. Analizirana su vratila od aluminijuma i kompozitnih karbonskih vlakana u kombinaciji sa epoksidnom smolom. U radu se predlaže višekriterijumski pristup (MCDM) za izbor optimalnog materijala prenosnog vratila. Istaknuto je koliko je ova metoda pogodna za analize ovog tipa jer u izbor uključuje uticaj brojnih kvalitativnih i kvantitativnih svojstava materijala.

KLJUČNE REČI: *višekriterijumsko odlučivanje, vratilo, materijal, kompozit*

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INTRODUCTION

Metal drive shafts can have mass limitations, low critical speeds, and potentially destructive vibrations. Composite drive shafts, thanks to the nature of composites, in which the specific modulus of elasticity is higher (modulus to density ratio) than in metal, can be a good replacement. Composite drive shafts offer excellent vibration damping, reduced wear of drive assembly components, are less susceptible to the effects of stress concentration, reduce installation time, inventory costs, maintenance, etc. [1]. Replacing conventional metal structures with composite structures has many advantages, due to higher specific stiffness and higher specific strength of composite materials [2,3]. The process of filament winding is used in the production of composite drive shafts. And in order to achieve an efficient design, it is done by choosing the appropriate variables, such as the inner radius, the thickness of the layers, the number of layers, the orientation of the fibers, the angle and the order of stacking the layers [4]. In the optimal drive shaft design, these variables are limited by lateral natural frequencies, torsional vibrations, torsional strength, torsion and bending of the shaft, as well as shaft fatigue due to torsion [5-7]. Material has an important role in the design process. Choosing the right material for a particular product is one of the vital tasks for engineers. In order to meet the final requirements of the product, engineers and designers need to analyze the characteristics of different materials and identify the appropriate material. Due to the presence of a large number of materials with different properties, the process of material selection is a complicated and time-consuming task. There is a need for systematization and an efficient approach to select the best alternative material for a given product. The conflicting nature of the material selection evaluation criteria can be resolved using the Multi-Criteria Decision-Making (MCDM) method. The work of Emovon and Oghenenyerovwho (2020) presents a methodological review of the application of MCDM in material selection. The study reviewed a total of 55 papers, published from 1994 to 2019, which were reviewed mainly in high-ranking journals. The results of the analysis showed that the hybrid method combined with two or more MCDM methods is the most applied material selection technique in a particular field of application, and that the MCDM technique is a very useful tool in decision making regarding material selection [8]. The work of Okokpujie et al. (2020) focuses on the implementation of the MCDM for the process of selecting the appropriate material for the development of a horizontal wind turbine blade. The research considers four alternatives, namely aluminum alloy, stainless steel, fiberglass and mild steel. In this paper, a quantitative research approach using AHP and TOPSIS multicriteria decision-making methods was used [9]. Anojkumar et al. (2014) deal with the selection of the optimal material for pipes for use in the sugar industry, from a set of five alternative materials and seven evaluation criteria. The paper discusses different perceptions of methodologies in the problem of material selection, using MCDM. The proposed models FAHP-TOPSIS, FAHP-VIKOR, FAHP-ELECTRE, FAHP-PROMTHEE and VIKOR are simple, practical, precise and efficient tools that help decision makers to choose the right material from alternative materials [10].

The aim of this paper is a multicriteria approach (MCDM) for the selection of the optimal material of the transmission shaft. Aluminum and composite carbon fiber shaft in combination with epoxy resin were analyzed, taking into account seven evaluation criteria: Elasticity modulus E_1 and E_2, sliding modulus, G_{12}, ratio E_1/ρ, weight m, natural frequency f_s, critical speed n_{kr}.

The drive shaft of the car Nissan 350Z series 946-244 was considered. The geometric measurements of the analyzed shaft are: the length of the shaft is 1.5 m, the mean diameter of the shaft is 0.08 m, the wall thickness of the annular cross-section of the shaft is 0.002 m. the shaft is shown in Figure 1.

Figure 1 Nissan 350Z drive shaft [11]

The values of natural frequencies and critical speeds in this work were obtained numerically, using the finite element method. The analysis was carried out using the software FEMAP version 2021.2. The critical speed of the drive shaft of a light-duty passenger vehicle should be greater than 6500 min^{-1}.

1. SELECTION OF OPTIMAL SHAFT MATERIALS USING MCDM

The analysis considered four different materials (Aluminum, USN 150 carbon/epoxy, HS carbon/epoxy, HM carbon/epoxy) for shaft construction and analyzed the impact of seven characteristic values (performance) which are assigned the role of criteria in the multi-criteria decision-making process. The method of additive weighting methods (SAW Simple Additive Weighting Method) was applied in this paper. The SAW method belongs to the relatively simple methods of multicriteria decision-making, but it also belongs to the group of methods that provide relatively reliable estimates of the rank of the considered alternatives. An important element in choosing this method is, in addition to its simplicity, the fact that this procedure takes into account the so-called weighting factors.

Table 1 shows the values of the selected quantities (criteria) for the considered materials. These are also the values (x_{ij}) that form the so-called Decision Matrix.

The procedure of normalization of data from the Table 1 is carried out using the following expressions (1), for max type criteria, and (2), for min type criteria, depending on whether it is a criterion of maximization or minimization type (in the considered example, all selected sizes, ie adopted criteria are of the maximization type, except for the mass of material). One of the criteria planned in the analysis was supposed to be the price of a certain material on the market, but due to the current turbulent economic trends that affect the great instability and comparability of prices, this criterion was omitted. It is planned that, with the calming of events on the world material market, this criterion will be a supplement and part of this analysis:

$$r_{ij} = \frac{x_{ij} - x_j^{\min}}{x_j^{\max} - x_j^{\min}} \tag{1}$$

$$r_{ij} = \frac{x_j^{\max} - x_{ij}}{x_j^{\max} - x_j^{\min}} \tag{2}$$

Table 1 *Values of the considered quantities - criteria for selected materials (x_{ij})*

	Criteria						
	Elasticity modulus E_1, MPa	Elasticity modulus E_2, MPa	Sliding modulus G_{12}, MPa	Ratio E_1/ρ, MPa/kg	weight m, kg	natural frequency f_s, Hz	critical speed n_{kr}, Hz
Aluminum	72000	72000	27000	28	0.6	222.67	13360
USN 150 carbon /epoxy	131600	8200	4500	84.9	0.36	325.46	19527
HS carbon /epoxy	134000	7000	5800	83.7	0.37	335.15	20109
HM carbon /epoxy	190000	7700	4200	118.75	0.37	354.08	21245
type of criteria	max	max	max	max	min	max	max

The values of the normalized data in Table 1 are shown in Table 2.

Table 2 *Normalized values of the considered quantities - criteria for selected materials (r_{ij})*

	k1	k2	k3	k4	k5	k6	k7
Aluminum	0	1	1	0	1	0	0
USN 150 carbon /epoxy	0.505085	0.018462	0.013158	0.626997	0	0.782208	0.782118
HS carbon /epoxy	0.525424	0	0.070175	0.613774	0.041667	0.855947	0.855929
HM carbon /epoxy	1	0.010769	0	1	0.041667	1	1

The weighting coefficients (Wi') of the criteria were determined in two variants using the Saaty procedure [12]. In the first variant, the priority in importance was given to some criteria (sizes) such as k4, k6 and k7, while some were less significant, such as k3. An overview of the Dominant Matrix, for this variant, is given in the Table 3.

Table 3 *Dominant matrix - the first variant*

	k1	k2	k3	k4	k5	k6	k7	Wi
k1	1	1	3	0	0	0	0	5
k2	1	1	3	0	0	0	0	5
k3	0	0	1	0	0	0	0	1
k4	3	3	5	1	2	1	1	16
k5	2	2	4	0	1	0	0	9
k6	3	3	5	1	2	1	1	16
k7	3	3	5	1	2	1	1	16

In the second variant considered, all criteria were equal in importance. The dominant matrix for this variant of the relationship of importance of the criteria is shown in the Table 4.

Table 4 *Dominant matrix - the second variant*

	k1	k2	k3	k4	k5	k6	k7	Wi
k1	1	1	1	1	1	1	1	7
k2	1	1	1	1	1	1	1	7
k3	1	1	1	1	1	1	1	7
k4	1	1	1	1	1	1	1	7
k5	1	1	1	1	1	1	1	7
k6	1	1	1	1	1	1	1	7
k7	1	1	1	1	1	1	1	7

The values of the relative weighting coefficients are shown in the diagram in Figure 2.

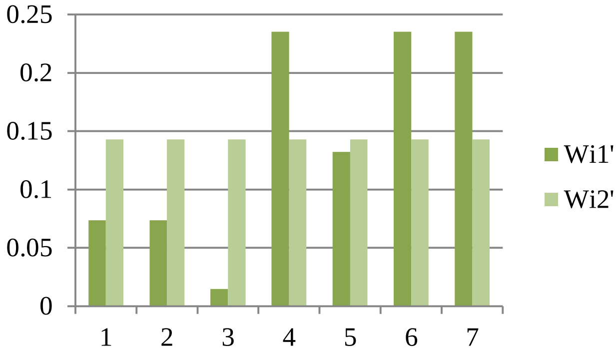

Figure 2 Relative weight coefficients in two variants

Using the procedure implied by the SAW method, the aggregate characteristics for each of the four considered materials were determined for both variants of weight coefficients. The diagram shown in Figure 3 clearly shows that the fourth considered material (HM carbon / epoxy) in both cases has the highest cumulative characteristic, ie the highest score within the conducted multicriteria analysis.

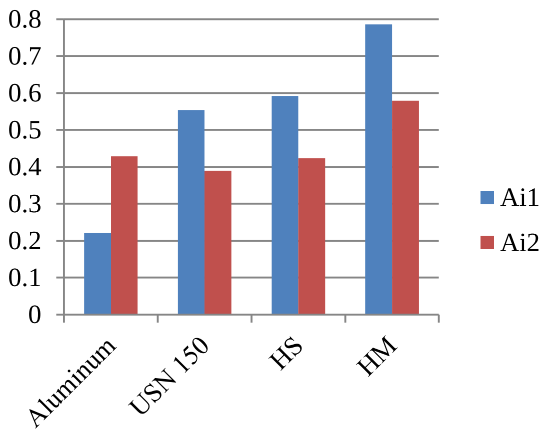

Figure 3 Aggregate characteristics in both considered variants

2. CONCLUSIONS

Ranking and selecting the best material in the product design process is a very important and complex task. The procedure of analysis of composite materials, which was the topic of this paper, is even more complex. Such materials require a multi-criteria approach in the selection. Such an approach provides an opportunity for the designer to change the design of the product already in the design phase and thus achieve an improved version of the same, and all this leads to a reduction in production costs. The aim of this paper was to select the optimal material for the transmission shaft, from the aspect of dynamic stability, for which the SAW method was used as one of the methods of multicriteria decision making. Four different materials (aluminum and three composite materials - USN 150, HS and HM carbon/epoxy) were considered. Based on the presented analysis of the mentioned materials and the evaluation of seven selected characteristics, the shaft made of HM carbon/epoxy showed the best results. The analysis was performed for two variants of weight coefficients and in both cases an identical conclusion was reached.

The next step in the design process would be the analysis of the economic factor (material prices), which will be the subject of future research in this area.

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