

Influence of angles of fiber orientation on improving the characteristics of composite cardan shaft using factorial experiment

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Abstract. Composite shafts in compare with steel ones are characterized by lower weight, lower values of stress and deformation, extremely harmonic vibration damping and higher values of natural frequencies. The analysis of the optimal design of composite cardan shafts has shown that the load capacity of shaft is greatly influenced by type of material and the angle of orientation of the fibers. In this study the influence of the fiber orientation in layers of the composite laminar cardan shaft of truck on the angle of twist using a factorial experiment was analyzed. Analyzed shaft is composed of nine layers wherein the first layer is of aluminum, and the rest of carbon/epoxy composites with different angles of fiber orientation (-45° , 0° , 45° and 90°). By using the factorial experiment the optimal variant angles of fiber orientation is obtained and the effect of each layer on the angle of twist of drive shaft. The results obtained show that the factorial experiment could be applied on optimization of composite cardan shaft which influences on the improvement of the characteristics of the screw shaft.

1. Introduction

Industry needs a continuous development of new technologies and materials, and its aim is to achieve a greater strength and stiffness of the material, but also reduce the weight of components and complete structures. Better properties, compared to the properties of the individual materials, are achieved by connecting two or more separate materials in a single - composite material. The desired characteristics of a newly created composite material are achieved by a combination of different materials. The application of composite materials began in the aerospace industry and in recent years it has had a strong presence in various industries. The use of composite materials has led to extraordinary achievements in the automotive, aerospace and military industries, medicine, prosthetics, sport, etc. These achievements are reflected in the improvement of material characteristics, as follows: fatigue resistance and corrosion resistance, of high specific strength and high modulus, as well as, in the request of the energy decrease due to weight reduction [1-6].

The application of composite materials increases from year to year in automotive industry, because the substitution of steel parts with composite parts reduces the weight of the individual parts, as well as the vehicles in general. The reduced vehicle weight affects the reduced fuel consumption, less tire wear, reduced CO₂ emissions and environmental protection [6-8]. A good example is the use of composite materials instead of steel for shaft making. The optimization of composite materials for making shafts with other influential parameters on the characteristics of the composite shaft is



necessary in order to obtain an optimum combination of materials with the best characteristics in the shortest possible time.

In recent years, the use of statistical methods of planning experiments has significantly increased, thus achieving the efficiency of the experimentation process. The better results are achieved by applying optimization methods with fewer repetitions of the experiment, which also reduces the cost of testing. Commonly used optimization methods are: Taguchi method, Factorial technique, Grey Taguchi method, Response Surface Methodology, Artificial Neural Networks and others. Numerous authors have, in their papers, analysed the application of composite materials for making shafts, by selection of optimum design and orientation of the fibres.

Rangaswamy and Vijayarangan performed the design optimization of composite drive shafts or power transmitters. They designed one-piece composite drive shaft to replace the conventional steel cardan shaft on the car. They used composite materials: E-glass/epoxy and high modulus (HM) carbon/epoxy. They applied the genetic algorithm (GA) technique for solving and optimizing design of composite drive shafts. The purpose of using GA in this paper is to reduce the weight of the shaft, which is subjected to restrictions, such as torque transmission, torsional buckling capacities and fundamental lateral natural frequency. The weight savings with composite E-glass/epoxy drive shaft are 48.36% in comparison to the steel shaft, while the weight savings of the shaft, made of HM carbon/epoxy composite, are 86.90% in comparison to the steel shaft. The results showed that the GA can be effectively and efficiently used in other complex and realistic designs, as well as in engineering application [9].

Moorthy et al. replaced the conventional steel drive shaft of the car with a suitable composite drive shaft. It is known that conventional drive shafts are made of two parts due to the reduction of bending natural frequency, and in this research the authors used the one-piece composite drive shaft for the purpose of reducing the overall weight. The analysed composite shafts are made of carbon/epoxy and kevlar/epoxy, and they are compared with steel shafts. The values for torsional strength, bending natural frequency and torsional buckling are compared. They compared the weight, number of layers and sequence of layers, where they concluded that the use of carbon/epoxy drive shaft, instead of conventional drive shaft, led to the weight savings of 89.756%, with barely half the wall thickness of a conventional steel shaft. Their operation is based exclusively on the analytical calculation, and the use of the layers distribution by using tables which refer to 60% of volume and 0.13 mm thickness. This approach focuses on the distribution of the layers in standard orientations 0°, 90°, 45° and -45° for considered composites [10].

Kumar Rompicharla and Rambabu replaced the conventional two-piece steel drive shaft with the shaft made of kevlar/epoxy composite material. The design parameters are optimized in order to reduce the weight of the drive shaft. The authors investigated the deflection, stresses, and natural frequencies under subjected loads by using finite element analysis (FEA). They came to the conclusion that the use of composite materials reduces the weight by about 28% compared to the conventional steel shafts. Taking into consideration the weight reduction, deformation, shear stress and resonant frequency, they concluded that the kevlar/epoxy composite has good properties and it can be used as a substitute for steel [11].

Hargude and Ghatage performed the optimization of design parameters of the composite drive shaft, which replaced the conventional steel shafts for cars, by using a genetic algorithm. The parameters such as layer thickness, number of plies and stacking sequence are optimized for E-glass/epoxy and HM-carbon/epoxy shafts in order to reduce the weight of a composite shaft which is subjected to limitations such as the torque transmission, torsional buckling load and fundamental natural frequency. The use of composite materials and techniques of optimization resulted in a significant weight reduction in the range of 48% to 86% compared to a conventional steel shaft [8].

Madhu et al. performed the suitability check of one-piece composite drive shaft with different combinations of composite material in order to meet the functional requirements. Models of the drive shaft are made of steel SMC45, kevlar49/epoxy and carbon composite HM and they are analysed by the finite element analysis by using ANSYS software 10. It is noted that the composite shafts have

better shear strength and bending natural frequency compared to a steel. Kevlar49/epoxy has better strength in the critical torsion compared to other composites. They compared the results of the finite element analysis with analytical values and they concluded that the one-piece composite drive shaft was better for automotive application [12].

There are a large number of papers and researchers dealing with this problem, but from this brief review it can be concluded that there is a tendency to replace the two-piece steel cardan drive shafts with one-piece composite shafts. The researchers have generally performed optimization of composite cardan drive shafts by using a genetic algorithm in order to find the best combination of materials. This literature review has shown that there is no application of factorial experiment for optimization of the composite shaft. Also, it is noted that the researchers concluded that the replacement of the conventional drive shaft with a carbon/epoxy composite shaft led to the great weight savings, even up to 90% [8, 10].

The basic research in this paper is focused on finding the optimum value of the angles of orientation of the fibre layers of the laminar composite cardan shaft by using a factorial experiment. The model of composite shaft is made of Al/carbon/epoxy in FEMAP and NeNASTRAN programs.

2. Composite cardan shafts

Cardan shafts are special types of transmissions that are widely used in today's vehicles. Their main feature is that they allow torque transmission when shafts are connected with this transmission spaciouly under a constant variable angle, allowing their relative motion. The cardan shaft is required to: have ability to transfer torque with the possibility of changing the angle between certain shafts, the ability to change the length of cardan transmission, at uniform rotation of the drive part of the shaft, the uniform rotation of the upper part of the shaft [13]. Systems of power transmission and transformation of torque with motor vehicles have the main task to transfer the power drive unit to drive wheels or excavator sprocket, with appropriate transformation of torque. The aim of power transmission system, under all operating conditions of the vehicle, is to ensure full utilization of engine power. There is an intensive work with modern vehicles, and trucks, to reduce the weight of the vehicle, primarily in order to save fuel and to increase starting, by applying aluminum or plastic materials in the vehicle structure and the engine or by applying other lightweight materials with improved strength (light alloy, composite materials and etc.) [14, 15].

Substituting composite structure instead of conventional metal construction has advantages due to a higher specific stiffness and higher specific strength of composite materials. With the development of technology and the application of the composite materials, there is a tendency for two-piece steel drive (cardan) shafts to be replaced with one-piece composite shaft. The use of composite materials reduces the overall weight of the vehicle. Thereby, the laminar composites have advantage due to their high specific stiffness. A composite drive shafts have a longer lifespan of the drive mechanism with a higher critical velocity [8, 11].

The cardan shaft of the truck TURBO ZETA 85.14B was tested in this paper. The two-piece steel shaft was replaced by a one-piece hybrid aluminum/carbon/epoxy composite shaft. Investigated cardan shaft was composed of nine layers (a first layer of Al, and the rest of carbon/epoxy composites with different angles of fibre orientation). Mechanical characteristics of the tested materials are given in Table 1 (for carbon/epoxy composite) and Table 2 (for aluminum). The basic dimensions of one-piece cardan shaft are: the length of the shaft is 1.35 m and the mean radius of the shaft is 0.041 m and wall thickness of the ring shaped cross section of the shaft is 0.003 m. The analysis of a factorial experiment was conducted based on the results obtained for the angle of twist of the composite cardan shaft by using the program FEMAP and NeNASTRAN [16]. The angles of twist of the composite cardan shaft were analysed in the MINITAB 16 software by means of general full factorial method.

Table 1. Basic characteristics of the carbon fibres/epoxy composite (USN150).

	Mark (Units)	Value
Longitudinal modulus	E_1 (GPa)	131.6
Transverse modulus	E_2 (GPa)	8.20
Shear modulus	G_{23} (GPa)	4.5
Shear modulus	G_{12} (GPa)	4.5
Poisson's ratio	ν	0.31
Density	ρ (kg/m ³)	1550
Composite layer thickness	t_{s1} (mm)	0.125

Table 2. Basic characteristics of the aluminum tube.

	Mark (Units)	Value
Tensile modulus	E (GPa)	72
Shear modulus	G (GPa)	27
Density	ρ (kg/m ³)	2695
Yielding strength	R_e (MPa)	325
Shear strength	S_{Al} (MPa)	210
Thickness of the aluminum tube	t_{Al} (mm)	2.5

3. Experiment

3.1. Factorial experiment

The method of planning experiment represents the starting point of experimental research. The adequate planning of the experiment and the analysis of its results facilitates the process of making conclusion about the observed problems. The problems and objectives of the experiment are determined in the planning phase of the experiment, then the factors, that could significantly affect the characteristics of the monitored process, are being selected and the effect levels of these factors are being chosen. The careful planning of experiments is necessary when using statistical methods to make certain conclusions from the available data.

The factorial experiment represents the statistical method for the processing of the experimental results when the subject matter is affected by several factors with multiple levels. The factorial experiment 3^n has n factors, each of which is with three levels, while 2^n has n factors, each of which is with two levels. The factorial experiment indicates the product of factor levels, which show the total number of combinations of factor levels [17, 18]. The application of factorial experiment is to improve the characteristics of laminar composite cardan drive shaft. In this research, the optimization of fibre orientation angle on layers of laminar composite cardan shaft was performed in order to obtain a minimum value of the angle of twist of the cardan shaft.

Table 3 shows the selected factors and their levels which affect the angle of twist of cardan shaft. In this paper, nine factors are considered, the first of which is at one level, while the others are at four levels. The first factor (A) represents the first layer of the laminar composite material of the cardan shaft and it is the aluminum layer (that is why there is no value of the fibre orientation angle in Table 3). Other considered factors are the layers of carbon/epoxy composite and their layers are angles of fibre orientation (-45° , 0° , 45° and 90°). The marking of these factors are values of the angles of fibre orientation on the layers, as follows: B - the second layer, C - the third layer, D - the fourth layer, E - the fifth layer, F - in the sixth layer, G - the seventh layer, H - the eighth layer and J - the ninth layer, of composite laminar cardan shaft.

Table 3. Considered factors and their levels.

<i>Factors</i>	A	B (°)	C (°)	D (°)	E (°)	F (°)	G (°)	H (°)	J (°)
1	/	-45	-45	-45	-45	-45	-45	-45	-45
2	/	0	0	0	0	0	0	0	0
3	/	45	45	45	45	45	45	45	45
4	/	90	90	90	90	90	90	90	90

The software program Minitab 16 was used to optimize the angle of fibres orientation of tested laminar composite cardan shaft. The experimental plan is defined as a set of experimental or measurement points which are expressed by plan, i.e. matrix; Taguchi L32 orthogonal matrix has been selected in this case (Table 4)

Table 4. Considered factors and their levels.

<i>Factors</i>	A (°)	B (°)	C (°)	D (°)	E (°)	F (°)	G (°)	H (°)	J (°)	<i>Angle of twist (rad)</i>
1	0	-45	-45	-45	-45	-45	-45	-45	-45	0.171
2	0	-45	0	0	0	0	0	0	0	0.209
3	0	-45	45	45	45	45	45	45	45	0.167
4	0	-45	90	90	90	90	90	90	90	0.209
5	0	0	-45	-45	0	0	45	45	90	0.186
6	0	0	0	0	-45	-45	90	90	45	0.193
7	0	0	45	45	90	90	-45	-45	0	0.186
8	0	0	90	90	45	45	0	0	-45	0.193
9	0	45	-45	0	45	90	-45	0	45	0.180
10	0	45	0	-45	90	45	0	-45	90	0.186
11	0	45	45	90	-45	0	45	90	-45	0.180
12	0	45	90	45	0	-45	90	45	0	0.187
13	0	90	-45	0	90	45	45	90	0	0.193
14	0	90	0	-45	45	90	90	45	-45	0.185
15	0	90	45	90	0	-45	-45	0	90	0.193
16	0	90	90	45	-45	0	0	-45	45	0.186
17	0	-45	-45	90	-45	90	0	45	0	0.187
18	0	-45	0	45	0	45	-45	90	-45	0.179
19	0	-45	45	0	45	0	90	-45	90	0.186
20	0	-45	90	-45	90	-45	45	0	45	0.179
21	0	0	-45	90	0	45	90	-45	45	0.185
22	0	0	0	45	-45	90	45	0	90	0.193
23	0	0	45	0	90	-45	0	45	-45	0.186
24	0	0	90	-45	45	0	-45	90	0	0.193
25	0	45	-45	45	45	-45	0	90	90	0.180
26	0	45	0	90	90	0	-45	45	45	0.186
27	0	45	45	-45	-45	45	90	0	0	0.180
28	0	45	90	0	0	90	45	-45	-45	0.186
29	0	90	-45	45	90	0	90	0	-45	0.193
30	0	90	0	90	45	-45	45	-45	0	0.186
31	0	90	45	-45	0	90	0	90	45	0.193
32	0	90	90	0	-45	45	-45	45	90	0.185

3.2. Discussion and analysis of the results

The analysis of the obtained results was performed by using a factorial experiment, namely a general full factorial. In this analysis, since the first factor was on one level, it was not taken into consideration in order to obtain a relevant data. Analysis of variance (ANOVA) is a statistical method used to examine the effect of one or more independent variables on one dependent variable. The term analysis of variance describes a group of statistical procedures developed by the British statistician Fisher. The results of ANOVA analysis of laminar composite cardan shaft are shown in Table 5.

Table 5. Analysis of variance of Al/carbon/epoxy.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Pr (%)
B	3	0.0002156	0.0002156	0.0000719	5.51	0.029	9.55
C	3	0.0002486	0.0002486	0.0000829	6.36	0.021	11.02
D	3	0.0002706	0.0002706	0.0000902	6.92	0.017	11.99
E	3	0.0002603	0.0002603	0.0000868	6.66	0.019	11.54
F	3	0.0002851	0.0002851	0.0000950	7.29	0.015	12.63
G	3	0.0002828	0.0002828	0.0000943	7.24	0.015	12.53
H	3	0.0003068	0.0003068	0.0001023	7.85	0.012	13.60
J	3	0.0002956	0.0002956	0.0000985	7.56	0.013	13.10
Error	7	0.0000912	0.0000912	0.0000130			4.04
Total	31	0.0022567					100

DF - degree of freedom, Seq SS - Sequential sum of squares, Adj SS - Adjusted sum of squares, Adj MS - Adjusted mean square, F - value, P - percentage of contribution

Based on the performed analysis and the calculated percentage effect of the factors, it can be concluded that factors H (13.60%) and J (13.10%) have the largest influence. Generally, all factors have approximately the same percentage values of influence on the angle of twist of the composite cardan shaft, while the error has a much smaller impact (4.04%).

Also, the influence of factors can be determined by using Fisher's distribution for 99%, 95%, or 90% probability, on the basis of the number of degrees of freedom factors and the number of degrees of freedom error. F values, obtained by the analysis, must be greater than the values of Fisher's distribution for the appropriate number of degrees of freedom. Based on Fisher's distribution for a 95% probability ($F = 4.35$), it can be concluded that all considered factors affect the angle of twist of the composite cardan shaft.

The graphical representation of experimental values of the angle of twist of cardan shaft are shown in figure 1. The optimal levels of factors can be determined based on the shown main effects of the factors (figure 1) on the angle of twist.

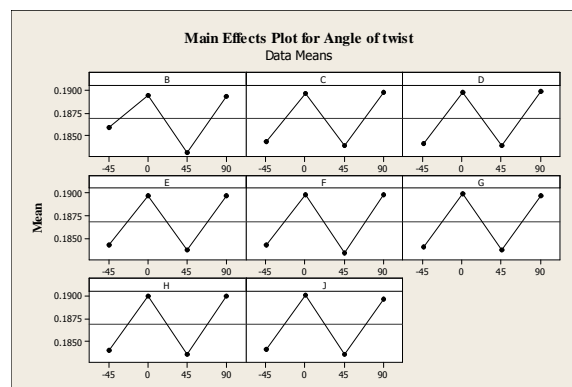


Figure 1. Graphic representation of the effects of the main factors on the angle of twist.

The optimal variant of the fibre orientation angle on layers of laminar composite cardan shaft is the one that is obtained by a minimum value of the angle of twist of the composite cardan shaft, which affects the improvement of characteristics of the shaft. Based on the effect factor of angle of twist, it can be concluded that the minimum value of the angle of twist of the composite cardan shaft is obtained when all values of the fibre orientation angle are in all layers of carbon/epoxy composite of 45° . It can also be noticed that (figure 1) there is a small difference between fibre orientation angles of $+45^{\circ}$ and -45° . Figures 2 and 3 show the effect of the most influential factors on the angle of twist of the tested composite cardan shaft.

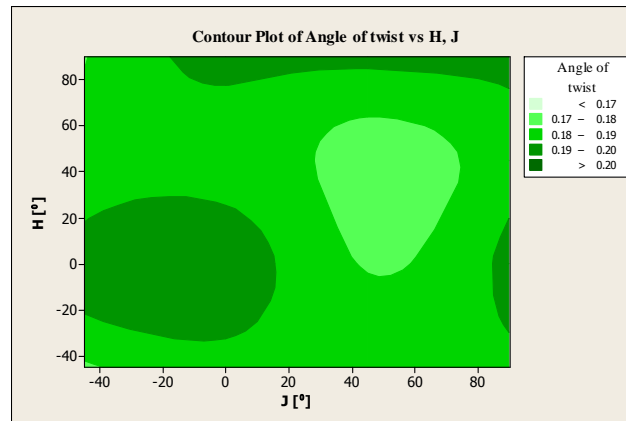


Figure 2. 2D view of the angle of twist depending on the most influential factors.

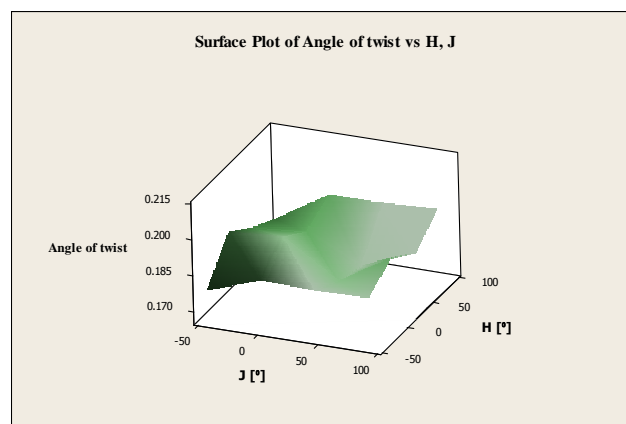


Figure 3. 3D view of the angle of twist depending on the most influential factors.

Figure 2 and 3 show that the minimum value of the angle of twist for the most influential factors is within the range of 0° to 60° , while the maximum value of the twist of cardan shaft can be obtained at the following angles of fibre orientation: for factor H within the range of -20° to 20° and at 90° , and for the factor J from -40° to 0° and -20° to 90° .

3.3. Regression analysis

The model of liner regression is obtained by using the statistical software Minitab 16. The linear regression model is developed to establish a correlation between significant conditions obtained from the ANOVA analysis. The regression equation obtained by the analysis of statistical data for the angle of twist of cardan shaft is as following:

$$\begin{aligned} \text{Angle of twist} = & 0.183 + 0.000009 \cdot B + 0.000023 \cdot C + 0.000025 \cdot D + \\ & + 0.000022 \cdot E + 0.000023 \cdot F + 0.000024 \cdot G + 0.000026 \cdot H + 0.000023 \cdot J \end{aligned} \quad (1)$$

Determining the coefficient of linear equation enables the required prediction to be performed. Based on the analysis of the general full factorial, the optimal values of the angle of fibre orientation are for all layers of carbon/epoxy composites of $+45^0$. The angle of twist of 0.171008 rad is obtained by repeating the experiment for this combination of angles of fibre orientation of cardan shaft.

The optimal variant of angles of fibre orientation $Al/[\pm 45]_4$, is obtained by the analysis in the programs FEMAP and NeNASTRAN for the cardan shaft made of Al/carbon/epoxy composite, and the angle of twist for those values is 0.161 rad [16]. The deviation values of angles of twist obtained by the general full factorial and in the programs FEMAP and NeNASTRAN is 6.216 %.

4. Conclusion

Based on the analysis of general full factorial, the optimization of the cardan shaft was performed in the program Minitab 16 in order to improve its characteristics and it is concluded that all considered factors approximately equally affect the angle of twist of composite cardan shaft.

The optimal variant of angles of fibre orientation on the layers of laminar composite cardan shaft is the one by which the minimum value of angle of twist of cardan composite shaft is obtained, which affects the characteristics of the shaft itself. The optimal value, obtained by this analysis, is that all angles of fibre orientation are in the layers of carbon/epoxy composite of $+45^0$.

Based on the optimal values of the fibre orientation angle and by using this analysis, it can be concluded that the deviation values of the angle of twist of cardan shaft obtained by using programs FEMAP and NeNASTRAN of the values obtained by analysis of general full factorial is 6.216%. This deviation shows that the factorial analysis is acceptable and that it can be used to determine the optimal values of fibre orientation angle, or to optimize the composite cardan shaft.

Based on this study and literature review, it can be concluded that further research could be performed in order to optimize the composite drive shaft, where the optimization of other parameters would be performed.

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References

- [1] Stojanović B, Babić M, Veličković S and Blagojević J 2016 Tribological Behavior of Aluminum Hybrid Composites Studied by Application of Factorial Techniques, *Tribological Transactions* **59**(3) 522-529
- [2] Jovanović M, Lazić V, Adamović D and Ratković N 2003 *Materials Science*, Faculty of Mechanical Engineering University of Kragujevac
- [3] Djordjevic Z, Blagojevic M, Marjanovic V and Jovanovic S 2014 The Influence of Material Types on Twist Angles and Torsion Stability of a Composite Shaft, *Technical Gazette* **21**(5) 917-923
- [4] Stojanović B and Ivanović L 2015 Application of Aluminium Hybrid Composites in Automotive Industry, *Technical Gazette* **22**(1) 247-251
- [5] Moorthy R S, Mitiku Y and Sridhar K 2013 Design of Automobile Driveshaft using Carbon/Epoxy and Kevlar/Epoxy Composites, *American journal of Engineering Research* **2**(10) 173-179
- [6] Djordjević Z, Jovanović S, Stanojević M, Blagojević M and Veličković S 2017 *Optimization of Fiber Orientation Angle of a Hybrid Al/Composite Cardan Shaft*, 13th International Conference on Accomplishments in Mechanical and Industrial Engineering DEMI, Banja Luka, B&H, May 26-27, pp. 489-494
- [7] Djordjević Z, Jovanović S, Gavrilović O, Čatić D and Savić S 2016 *Biocomposites – Ecologically Acceptable Materials*, 1st International Conference on Quality of Life, Kragujevac, Serbia, June 9-10, pp. 267-270

- [8] Hargude N V and Ghatage K D 2012 An Overview of Genetic Algorithm Based Optimum Design of an Automotive Composite (E-Glass/Epoxy and HM-Carbon/Epoxy) Drive Shaft, *International Journal of Mechanical Engineering & Technology* **3**(1) 110-119
- [9] Rangaswamy T and Vijayarangan S 2005 Optimal Sizing and Stacking Sequence of Composite Drive Shafts, *Materials Science (Medžiagotyra)* **11**(2) 133-139
- [10] Moorthy R S, Mitiku Y and Sridhar K 2013 Design of Automobile Driveshaft using Carbon/Epoxy and Kevlar/Epoxy Composites, *American journal of Engineering Research* **2**(10) 173-179
- [11] Rompicharla R P K and Rambabu K 2012 Design and Optimization of Drive Shaft with Composite Materials, *International Journal of Modern Engineering Research* **2**(5) 3422-3428
- [12] Madhu K S, Darshan B H and Manjunath K 2013 Buckling Analysis of Composite Drive Shaft for Automotive Applications, *Journal of Innovative Research and Solutions* **1A**(2) 63-70
- [13] Stojanović B and Blagojević M 2015 *Mechanical Transmitters*, University of Kragujevac Faculty of Engineering
- [14] Satheesh Kumar Reddy P and Nagarajub C 2017 Weight Optimization and Finite Element Analysis of Composite Automotive Drive Shaft for Maximum Stiffness, *Materials Today: Proceedings* **4**(2) 2390–2396
- [15] Saravanan R, Vivek P and Vinod Kumar T 2016 Is Kevlar 29/Epoxy Composite an Alternate for Drive Shaft, *Journal of Advances in Mechanical Engineering and Science* **2**(3) 1-13
- [16] Djordjevic Z 2008 *Dynamic Conduct Composite Shafts*, University of Kragujevac Faculty of Engineering Kragujevac, PhD Thesis
- [17] Veličković S 2013 *Investigation of the Environmental Factors' Influence on the Mechanical Properties of Plastics*, University of Kragujevac Faculty of Engineering, MSc Thesis
- [18] Blagojević J, Djordjević Z and Veličković S 2017 *Application of Taguchi Methods with Optimization of Fibre Orientation Angle of Laminated Al/Aramid/Epoxy Composite Cardan Shaft*, 8th International Scientific Conference on Research and Development of Mechanical Elements and Systems IRMES, Trebinje, B&H, September 7-9, pp. 265-270