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APPLICATION OF TAGUCHI METHODS WITH OPTIMIZATION OF FIBRE ORIENTATION ANGLE OF LAMINATED AL/ARAMID/EPOXY COMPOSITE CARDAN SHAFT

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Abstract: *Optimization of fibre orientation angle of the laminated Al /aramid /epoxy composite cardan shaft using Taguchi methods was carried out in this paper. The aim of the study is to obtain values of fibre orientation angle at which the lowest value of angle of twist of shaft is obtained. The analysis of the fibre orientation angle of the laminated composite shaft has been carried out using ANOVA analysis. The laminated composite shaft consists of a layer of aluminum and eight layers of aramid /epoxy composite whose fibre orientation angle taken into consideration is -45°, 0°, 45° and 90°.*
To model the cardan shaft, programmes like FEMAP and NeNASTRAN were used, and they helped obtain angles of twist of Al /aramid /epoxy composite cardan shaft at appropriate factor levels. Predicted value of the angle of twist deviated from the experimental one by 1.805%, whereas the value obtained by confirmation test deviated by 1.491% from the experimental value of the angle of twist.

Key words*: Al /aramid /epoxy composite, cardan shaft, Taguchi method, fibre orientation angle, angle of twist.*

1. INTRODUCTION

The basis of the study of this paper is to determine the fibre orientation angle of the laminated Al /aramid /epoxy composite cardan shaft, more precisely, to find the optimal variation of the angles of the layers where the lowest value of the angle of twist of the shaft is obtained.
A review of the literature has shown that the two-piece steel cardan shafts are replaced by one-piece composite shafts due to the reduction of weight. A very large number of papers are referring to determining the fibre orientation angle of composite cardan shaft.
Rangaswamy and Vijayarangan performed the optimization of drive cardan shafts in the paper [1]. They used composite materials: E-glass/epoxy and HM carbon/epoxy. The weight savings for the composite E-glass/epoxy drive shaft is 48.36% compared to the steel shaft, while the weight savings of HM carbon/epoxy composites are 86.90% of the steel shaft.
In this paper [2], Dinesh and Anand Raju replaced the conventional two-piece steel drive shaft with one-piece E-glass/epoxy, HS carbon/epoxy and HM carbon/epoxy composite drive shafts. The shafts are subjected to restrictions, such as transmission torque, torsional buckling capacity and natural bending frequency. The weight savings of E-glass/epoxy, HS carbon/epoxy and HM carbon/epoxy composites are 48.36%, 86.90% and 86.90% of the weight of the steel shaft respectively.
Manjunath and *Rangaswamy* [3] performed the optimization of the layer stacking sequence of the composite multi-layers drive shaft by using PSO (*particle swarm optimization*) algorithm. They proposed the optimization process for the design of a multilayer single-piece drive composite shaft for a given torque, velocity and length in order to achieve minimum weight. The materials used for the one-piece drive shaft are: E-glass/epoxy, NM carbon/epoxy and boron/epoxy composites. They developed the PSOA program in MATLAB V 7 to optimize the layer stacking sequence.
Srinivasa Moorthy et al. [4] designed and analysed carbon/epoxy and kevlar/epoxy composite shafts under conditions of torsional strength, natural bending frequency and torsional buckling, and they compared them with a conventional steel drive shaft under the same conditions. The emphasis was on aspects such as weight saving, number of layers and distribution of the layers. There is a reduction of weight in both types of composites compared to high-quality steel SM45C, but the carbon / epoxy for manufacturing an automotive drive shaft has multiple advantages. Its work is based exclusively on the analytical calculation. This approach focuses on the distribution of layers with standard orientations of 0º, 90º, 45º + and -45º for the considered composites.
Kumar Rompicharla and *Rambabu* used kevlar / epoxy composite material of the cardan shaft [5]. They tried to determine the deflection, voltages, and natural bending frequency by using the Finite Element Methods (FEM). They concluded that the kevlar/epoxy composite had

good properties and that it could be used as a replacement for steel.

In this paper, Taguchi methods were used to determine the optimal variant of the factors. The fiber orientation angles of the layers of laminar composite shaft are factors, and the angle of twist of shaft is a response. The laminar composite shaft consists of a layer of aluminum and eight layers of aramid / epoxy composites. The shaft model and the values of angle of twist for the combined factor levels were obtained in the *FEMAP* and *NeNASTRAN* programs. The *Minitab 16* program was used for statistical processing of the results, and the confirmation of the experiment for determining the interval of the angle of twist of the composite shaft was used for the obtained optimal variant.

2. COMPOSITE CARDAN SHAFTS

The basic role of the cardan gears is transmission of the torque between shafts which are spatially at constantly variable angle, allowing their relative motion [6].

In modern aircrafts, airplanes, cars and boats, primarily in order to save the fuel and increase starting, intensive work is done to reduce the weight of the vehicle, by using aluminum or plastic materials in the construction of vehicles and engines or by using other lightweight materials of increased strength (light alloys, composite materials, etc.) [7, 8, 9]. The laminar composites have advantages due to their high specific stiffness. The composite drive shafts have a longer lifespan of the drive mechanism with a higher critical velocity [5, 10]. The fiber orientation angle in the laminar composite is shown in Figure 1 [1].

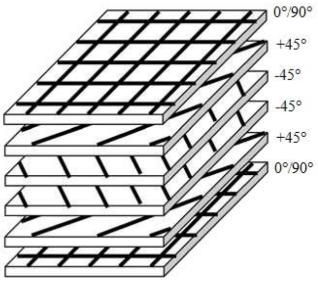

Fig.1: Fiber orientation angles

A laminar Al/aramid/epoxy composite shaft was used for testing in this paper. The basic characteristics of the aramid/epoxy composites are shown in Table 1, while the basic characteristics of the aluminum tubes are shown in Table 2 [11].

Table 1: Basic characteristics of aramid/epoxy composites

Longitudinal modulus	E_1	81.8 GPa
Transverse modulus	E_2	5.10 GPa
Shear modulus	G_{23}	1.82 GPa
Shear modulus	G_{12}	1.51 GPa
Poisson's ratio	ν	0.31
Density	ρ	1380 kg/m^3
Composite layer thickness	t_{sl}	0.12 mm

Table 2: Basic characteristics of aluminum tube

Tensile modulus	E	72000 MPa
Shear modulus	G	27000 MPa
Density	ρ	2659 kg/m^3
Tensile strength	R_m	350 MPa
Yielding strength	R_e	325 MPa
Shear strength		210MPa
Thickness of the aluminium tube		2.5 mm

3. TAGUCHI METHODS

Taguchi developed a method for designing experiments to examine how different parameters affect the mean value and variation of process performance characteristics that determine how well the process works. The experimental design that he proposed involves the use of orthogonal arrays for organization of parameters that affect the process and levels which are to be changed [12].

According to Taguchi, the selection of parameters is accomplished by methods of experiment planning, whereby Taguchi proposes using, along with ordinary indicators, a new quality indicator, the so-called signal/noise ratio (S/N).

The Taguchi method uses the loss function to calculate the deviation between the experimental value and the desired values. This loss function is converted into a S/N ratio. There are three types of S/N ratio: smaller the better, larger the better, and nominal the best, which serve to measure quality characteristics [13, 14, 15]. The S/N ratio the smaller the better was used in this paper:

$$S/\mathrm{N} = -10\log\left(\frac{1}{\mathrm{n}}\sum_{i}^{n} y_i^2\right), \quad (1)$$

where n is the repetition number of each trial and y_i is the result of the *i*-th experiment for each trial.

4. EXPERIMENTAL PART

The influence of the fibre orientation angle of aramid / epoxy composites on the angle of twist of the laminar combined Al/aramid/epoxy composite cardan shaft was tested in this paper. The aim of the paper is to obtain the values of the fibre orientation angle with the least torsion of the shaft.

The basic dimensions of the one-piece cardan shaft are: length of the shaft - 1.35 m, the mean radius of the shaft - 0.041 m, the thickness of the wall of the annular cross-section shaft - 0.003 m [11].

252 quadrangular finite elements of the shells were used for modelling the shaft. The maximum value of the maximum torque, at which the cardan shaft was tested, was 5000 Nm.

Table 3 shows the factors and levels of factors that are analysed. In this case, the factors are the fibre orientation angles of the composite laminar shaft. The first layer of the shaft is made of aluminum and the other layers are made of aramid/epoxy composites and the slopes of their fibres are on four levels (-45°, 0°, 45° and 90°).

Table 3: Factors and their levels

Factors (The fibre orientation angle)	Unit	Level			
		I	II	III	IV
(*A*) Layer 1	°	0	0	0	0
(*B*) Layer 2	°	-45	0	45	90
(*C*) Layer 3	°	-45	0	45	90
(*D*) Layer 4	°	-45	0	45	90
(*E*) Layer 5	°	-45	0	45	90
(*F*) Layer 6	°	-45	0	45	90
(*G*) Layer 7	°	-45	0	45	90
(*H*) Layer 8	°	-45	0	45	90
(*J*) Layer 9	°	-45	0	45	90

The first step in the application of Taguchi methods is to select the appropriate orthogonal array. Since a number of factors and levels are known, the appropriate orthogonal array *L32* has been selected for determining the optimal values of the fiber orientation angles of the layers of composite cardan shaft [16]. Since the factor *A* has only one level, it can be ignored in further analysis. The model of cardan shaft was made in the *FEMAP* and *NeNASTRAN* programs and the angles of twist of the Al/aramid/epoxy composite shaft are obtained by using those programs at the corresponding factor levels and they are shown in Table 4.

4.1. Statistical processing of the results

Table 4 shows the obtained S/N ratio values. S/N ratios were obtained by the use of *Minitab 16* using the equation (1). This equation is used when it tends to the minimum target value, and in this case it is the angle of twist of the laminar composite shaft.

Table 4: Orthogonal array L32 with experimental values of angle of twist and S/N values for Al/aramid/epoxy composite shaft

	A	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*J*	Angle of twist [rad]	*S/N* ratio [dB]
1	0	-45	-45	-45	-45	-45	-45	-45	-45	0.187	14.5632
2	0	-45	0	0	0	0	0	0	0	0.219	13.1911
3	0	-45	45	45	45	45	45	45	45	0.185	14.6566
4	0	-45	90	90	90	90	90	90	90	0.219	13.1911
5	0	0	-45	-45	0	0	45	45	90	0.201	13.9361
6	0	0	0	0	-45	-45	90	90	45	0.207	13.6806
7	0	0	45	45	90	90	-45	-45	0	0.202	13.8930
8	0	0	90	90	45	45	0	0	-45	0.207	13.6806
9	0	45	-45	0	45	90	-45	0	45	0.197	14.1107
10	0	45	0	-45	90	45	0	-45	90	0.202	13.8930
11	0	45	45	90	-45	0	45	90	-45	0.197	14.1107
12	0	45	90	45	0	-45	90	45	0	0.202	13.8930
13	0	90	-45	0	90	45	45	90	0	0.207	13.6806
14	0	90	0	-45	45	90	90	45	-45	0.201	13.9361
15	0	90	45	90	0	-45	-45	0	90	0.207	13.6806
16	0	90	90	45	-45	0	0	-45	45	0.201	13.9361
17	0	-45	-45	90	-45	90	0	45	0	0.202	13.8930
18	0	-45	0	45	0	45	-45	90	-45	0.196	14.1549
19	0	-45	45	0	45	0	90	-45	90	0.202	13.8930
20	0	-45	90	-45	90	-45	45	0	45	0.197	14.1107
21	0	0	-45	90	0	45	90	-45	45	0.201	13.9361
22	0	0	0	45	-45	90	45	0	90	0.207	13.6806
23	0	0	45	0	90	-45	0	45	-45	0.201	13.9361
24	0	0	90	-45	45	0	-45	90	0	0.207	13.6806
25	0	45	-45	45	45	-45	0	90	90	0.197	14.1107
26	0	45	0	90	90	0	-45	45	45	0.202	13.8930
27	0	45	45	-45	-45	45	90	0	0	0.197	14.1107
28	0	45	90	0	0	90	45	-45	-45	0.201	13.9361
29	0	90	-45	45	90	0	90	0	-45	0.207	13.6806
30	0	90	0	90	45	-45	45	-45	0	0.201	13.9361
31	0	90	45	-45	0	90	0	90	45	0.207	13.6806
32	0	90	90	0	-45	45	-45	45	90	0.201	13.9361

Based on the results of the S/N ratio, it can be determined which of the control factors has the greatest influence on the angle of twist of the one-piece composite shaft (Table 5). The optimal parameters of the angle of twist of these controlled factors can be determined based on the S/N ratios shown in Table 5 and Figure 2.

Parameter optimization of the angle of twist within the given factors and levels, considering the criterion "the smaller the better", gives the combination of control factors*: A1, B3, C3, D3, E3, F3, G3, H3* and *J3*. In other words, the combination of angles of aramid fiber slope is obtained in all layers of 45 ° for the lowest value of the angle of twist of Al/aramid/epoxy composite shaft.

Table 5: Response table for S/N ratio (for "the smaller the better" case)

Level	B	C	D	E	F	G	H	J
1	13.96	13.99	13.99	13.99	13.99	13.99	14.00	14.00
2	13.80	13.80	13.80	13.80	13.79	13.79	13.78	13.78
3	14.01	14.00	14.00	14.00	14.01	14.01	14.01	14.00
4	13.81	13.80	13.79	13.78	13.79	13.79	13.79	13.79
Delta	0.20	0.20	0.21	0.22	0.22	0.22	0.23	0.22
Rank	7	8	6	4	2	4	1	4

Experimental results are processed by applying the analysis of variance (*ANOVA*), which is used to identify the significance of the factors affecting the fibre orientation angles of the layers of composite shaft [17, 18]. The results of the ANOVA analysis are shown in Table 6.

Based on the ANOVA analysis of the S/N ratio, it can be concluded that all factors almost equally influence the angle of twist of the composite cardan shaft. Factor *H* has the greatest influence (14.46%), and factor *B* has the smallest influence (9.60%), while the influence of the error is almost negligible, amounting to 1.27%.

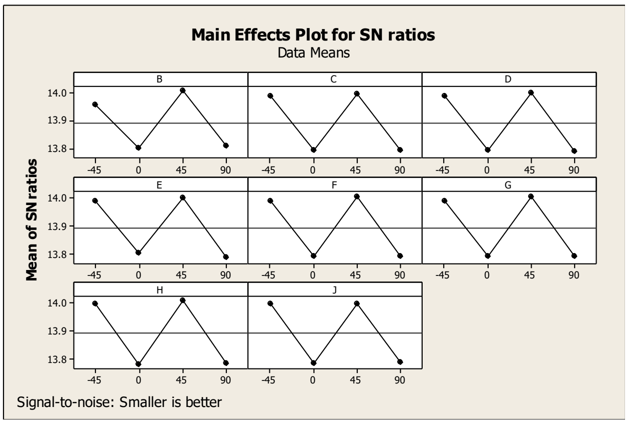

Fig.2: Diagram of the main effects of S/N ratio for angles of twist

Table 6: Results of ANOVA analysis of the S/N ratio

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Pr
B	3	0.25900	0.25900	0.086333	17.63	0.001	9.60
C	3	0.30876	0.30876	0.102920	21.01	0.001	11.44
D	3	0.32688	0.32688	0.108961	22.25	0.001	12.11
E	3	0.32737	0.32737	0.109125	22.28	0.001	12.13
F	3	0.34503	0.34503	0.115011	23.48	0.000	12.79
G	3	0.34500	0.34500	0.114999	23.48	0.000	12.78
H	3	0.39028	0.39028	0.130094	26.56	0.000	14.46
J	3	0.36207	0.36207	0.120691	24.64	0.000	13.42
Residual Error	7	0.03429	0.03429	0.004898			1.27
Total	31	2.69869					100

4.2. Confirmation of the experiment

Besides Taguchi optimization technique, the experiment confirmation is used to confirm the statistically obtained optimal factor variant. The predicted optimal value of the angle of twist is obtained by considering the individual effects of the factors and their levels (*A1*, *B3*, *C3*, *D3*, *E3*, *F3*, *G3*, *H3* and *J3*). Estimated optimal value of the angle of twist may be obtained from the equation [17, 19]:

$$\varphi_p = T_\varphi + (A1 - T_\varphi) + (B3 - T_\varphi) + (C3 - T_\varphi) + (D3 - T_\varphi) + (E3 - T_\varphi) + (F3 - T_\varphi) + (G3 - T_\varphi) + (H3 - T_\varphi) + (J3 - T_\varphi) \quad (2)$$

where Tφ is the mean value of the angle of twist, and *A1*, *B3, C3, D3, E3, F3, G3, H3* and *J3* are the *S/N* responses of the main factors at certain levels. The calculated optimal value of the angle of twist is 14.78333 dB.

The confidence interval for the predicted optimal value is calculated by using the terms:

$$CI = \sqrt{F_{\alpha:1,V_2} \cdot V_e \cdot \left(\frac{1}{n_{eff}} + \frac{1}{r} \right)}, \quad (3)$$

where $F_{\alpha:1,V_2}$ is the table value F за ниво пове for confidence level α, V_2 is degree of freedom of pooled error, V_e is pooled error variance, r is the number of repetitions, and n_{eff} is the number of effective measured results defined as:

$$n_{eff} = \frac{total\ experimental\ trials}{1 + (total\ degree\ of\ freedom\ of\ factors\ for\ prediction)}. \quad (4)$$

One confirmation experiment was performed for the evaluation of the performances of experimental tests for the angle of twist under optimal conditions, and because of that $r = 1$. For the level of reliability 95%, $\alpha = 0.05$ and $V_2 = 7$, value of $F_{\alpha;1,V_2} = 5.59$. A confidence interval (± 0.221) was calculated based on the equations (3) and (4).

The experiment for the levels of factors *A1, B3, C3, D3, E3, F3, G3, H3* and *J3* was performed and the result is compared with the values obtained by the previous equations and with the predicted values obtained in *Minitab 16* (Table 7).

The predicted value of the angle of twist of the shaft deviates from the experimental one by 1.805 %, while the value obtained by the confirmation of the experiment deviates by 1.491 % from the experimental value of the angle of twist.

Table 7: Results of the angle of twist and S/N ratio

	Predicted value	**Experiment confirmation value**	**Experimental value**
The angle of twist of the Al/aramid/epoxy composite cardan shaft [rad]	0.181719	0.1823	0.18506
***S/N* ratio [dB]**	14.7695	14.78333	14.65347

The optimal values of the fibre orientation angles are also obtained in the *FEMAP* and *NeNASTRAN* programs. The fibre orientation angle of the aramid / epoxy composite is Al/[± 454]. For these optimal fibre orientation angles, the value of the angle of twist of the Al/aramid/epoxy composite cardan shaft is 0.182 rad [12].

The deviation of the optimum value of the angle of twist of the composite shaft obtained by Taguchi method is 1,685 % of the optimal value obtained in the *FEMAP* and *NeNASTRAN* programs. The fibre orientation of the aramid / epoxy composite is Al/[± 454].

5. CONCLUSION

Based on the research in this paper, it can be concluded:

- ANOVA analysis of the S/N ratio shows that all factors have almost the same impact on the torsion of shaft and the error is 1.27 %.
- The lowest value of the angle of twist of the Al/aramid/epoxy composite cardan shaft by using the Taguchi method is obtained when the fibre orientation angles of aramid are in all layers of the aramide/epoxy composite + 45°.
- For optimal values of the fibre orientation in the *FEMAP* and *NeNASTRAN* programs, the obtained angle of twist of the shaft is 0.18506 rad (experimental value), and the obtained angle of twist in the *Minitab 16* program is 0.181719 rad (predicted value), while the angle of twist is obtained by confirming the experiment by 0.1823 rad.
- The predicted value of the experimental one deviates by 1.805 %, and the value of the angle of twist obtained by the experiment confirmation deviates by 1.491 % from the experimental one.
- The angle of twist obtained for the optimal variation of the fibre orientation angles in *FEMAP* and *NeNASTRAN* programs deviates from the angle of twist obtained by using the Taguchi method (experimental value) by 1.685 %.
- Taguchi methods can be used to analyse and optimize the fibre orientation angle of the laminar composite shaft layers that affect the angle of twist of the shaft.

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