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OPTIMIZATION AND PREDICTION OF SAFETY COEFFICIENT FOR SURFACE DURABILITY OF PLANETARY GEARBOX USING TAGUCHI DESIGN AND ARTIFICIAL NEURAL NETWORK

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Abstract: Optimization of parameters of planetary transmission by using Taguchi design was performed in this paper. Used values of safety coefficient for surface durability of internal gear of planetary gearbox were obtained by calculation. Considered parameters for optimizing are material, module and gear width. The influence of each parameter on the safety coefficient for surface durability of internal gear at 95% confidence interval was found by applying ANOVA analysis. The most influential parameter is gear module with a 74.034%, followed by the width of the gear with 16,858% and 8,874% material. Prediction of safety coefficient for surface durability of internal gear of planetary gearbox was performed by applying Artificial Neural Network (ANN).

Key words: Planetary gearbox, optimization, Taguchi design, ANN

1 INTRODUCTION

A special type of mechanical gear transmissions is planetary gear which are used when large transmission ratios, high degree of efficiency, durability in operation, low level of noise, and vibration are needed. Gear transmissions with movable axes are planetary gears. One simple planetary gear consists of two concentric central gears with immovable axes and of one or more satellites spinning around its axis and around the axis of the central gear. As for the central gears, the planetary gear may consist of: two central gears with external gearing; or one central gear with external gearing, and one central gear with internal gearing; or with both central gears with internal gearing [1, 2]. Planetary gears can be used with helicopters, car gearboxes, different industrial machines, tools, wristwatches, aviation and space industry, even with children's toys [3]. According to [4], these transmissions are denoted as follows: Taype of transmission: immovablemembre and basic members attached to external shafts.Type of transmission is marked with letters from A-E. Type of transmission: A has one-sided satellite, B and C have dual satellite, D has a pair of mutually meshed

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satellites, while the type E transmission has bevel gears [4]. The analysis of the transmission with the mark A_{ha}^{b} was performed in this paper.

Planetary gears are, due of its characteristics, the subject of many theoretical and experimental researches. For the simple planetary gear type A_{ha}^{b} , N. Ibrahimi has observed the change of transmission ratio and the degree of efficiency, which occured with the change of numbers of gear teeth of planetary gear. He has presented the results in the form of diagram and based on it, he has performed the optimization of the planetary gear [5]. J. Stefanović-Marinović et al. have performed the optimization of the simple planetary gear by observing the results obtained by the change of the number of gear teeth, module, number of satellites and gear width [6]. Sourabh Mandol et al. have obtained the linear regression model for predicting a nominal value of safety factor of the planetary gear by applying Taguchi method [7]. Khoualdia et al have used neural networks for monitoring and diagnosticating the condition of gears and bearings of rotating machines. For training of neural network, they have used time domain parameters and disadvantages of binary codes for input and output. For finding the best neural network, i.e. its architecture, they have applied two methods, Taguchi standard orthogonal array and Grey-Taguchi method. They have come to the conclusion that this kind of system can be successfully applied for monitoring and diagnostician the condition of rotational machines [8].

The influence of gear material, gear width, and the module on the safety coefficient for the surface durability of the internal gear of the planetary gear have been tested in this study by using Taguchi design experimental technique. The optimal values of the considered parameters are found in order to obtain satisfactory values of the safety coefficient for the surface durability of the internal planetary gear. While the influence of each parameter individually on the safety coefficient for the surface durability of the gear with internal gearing has been found by applying ANOVA analysis (analysis of variance). ANN has been applied in order to develop the prediction model for the safety coefficient for the surface durability of the gear with internal gearing and it has been compared to the regression model.

2 PLANETARY GEARBOX

The planetary gear type A_{ha}^{b} has been analysed within this paper. It can be seen that the transmission type A has been analysed, indicating that it is the transmission with one-sided satellite. The upper index ***b*** in the marking represents immovable member, while the lower indexes correspond to the basic members ***a*** and ***h*** which are attached to the external shafts. The first member in the lower index is ***h*** indicating that this member transfers the maximum torsion moment. It is obtained that the number of satellites is 3, a total transmission ratio is 4.5, while the number of teeth of gear with internal gearing is 70, by the calculation according to [3, 4 and 9]. A variation of the module, gear width, and gear material have been performed for the purpose of the optimization of this gear, and afterwards, its influence of the safety coefficient for the surface durability of the internal gear g has been monitored. The modules used in the optimization are: 2.5 mm; 2.75 mm and 3 mm; the width of the gears are: 27 mm, 30 mm and 33 mm; and the materials are: 16MnCr5 (Č4320), 28Cr4 (Č4134) and C15E (Č1221).

3 TAGUCHI METHOD

The simplest and the most efficient method for defining and researching all possible conditions, which include more factors, parameters, and variables in the experiment, is Taguchi method. Over the time, it has become the powerful and robust engineering tool by which the optimization and evaluation of the influential parameters are performed. In order to obtain more accurate results a well-organized experimental design is always needed [10-13].

Three factors are considered in this paper: material, module and gear width, and each of them has three levels. The parameters and their levels are given in Table 1.Taguchi's L27 Orthogonal Array has been used in the design of experiments and it is presented in Table 2. The table, also presents the results obtained by training with help of ANN method.

Table 1. *Levels of basic factors*

Control factors	Units	Level		
		I	II	III
A: Material	/	1 – 16MnCr5	2 – 28Cr4	3-C15E
B: Module	mm	2.25	2.50	2.75
C: Gear width	mm	27	30	33

Table 2. *Orthogonal matrix L27 with calculation results, calculated S/N ratios and ANN results*

	A	B	C	SH_a	S/N ratio	ANN	Regression
1	1	2.25	27	2.02	-6.10703	1.984226	2.045001
2	1	2.25	30	2.12	-6.52672	2.202744	2.155001
3	1	2.25	33	2.22	-6.92706	2.218981	2.265001
4	1	2.50	27	2.24	-7.00496	2.235081	2.275556
5	1	2.50	30	2.36	-7.45824	2.352311	2.385556
6	1	2.50	33	2.47	-7.85394	2.478868	2.495556
7	1	2.75	27	2.46	-7.8187	2.497408	2.506112
8	1	2.75	30	2.59	-8.266	2.594069	2.616112
9	1	2.75	33	2.71	-8.65939	2.710245	2.726112
10	2	2.25	27	2.05	-6.23508	2.050308	1.986112
11	2	2.25	30	2.15	-6.64877	2.139835	2.096112
12	2	2.25	33	2.25	-7.04365	2.239595	2.206112
13	2	2.50	27	2.28	-7.1587	2.24585	2.216667
14	2	2.50	30	2.39	-7.56796	2.392466	2.326667
15	2	2.50	33	2.50	-7.9588	2.627497	2.436667
16	2	2.75	27	2.50	-7.9588	2.461146	2.447223
17	2	2.75	30	2.63	-8.39911	2.629426	2.557223
18	2	2.75	33	2.75	-8.78665	2.74378	2.667223
19	3	2.25	27	1.92	-5.66602	1.924143	1.927223
20	3	2.25	30	2.02	-6.10703	2.009781	2.037223
21	3	2.25	33	2.11	-6.48565	2.112073	2.147223
22	3	2.50	27	2.13	-6.56759	2.129891	2.157778
23	3	2.50	30	2.24	-7.00496	2.267556	2.267778
24	3	2.50	33	2.34	-7.38432	2.425219	2.377778
25	3	2.75	27	2.34	-7.38432	2.33928	2.388334
26	3	2.75	30	2.46	-7.8187	2.463276	2.498334
27	3	2.75	33	2.57	-8.19866	2.621196	2.608334

3.1 Signal-to-Noise Ratio (S/N Ratio) and ANOVA

Taguchi method is a method that chooses the most suitable combination of the levels of controllable factors by using S/N tables and orthogonal arrays against the factor that form the variation. This method recommends the use of the S/N ratio to measure the quality characteristic deviating from the desired values and quality characteristics are: smaller-the-better, larger-the-better, or nominal-the-best. [10-13]

The S/N ratio for minimum safety coefficient for surface durability of internal gear, by using characteristic smaller-the-better, which can be calculated as logarithmic transformation of the loss function by the equation:

$$S/N = -10\log\frac{1}{n}\left(\sum y^2\right), \qquad (1)$$

where *y* is the safety coefficient for surface durability of internal gear obtained by the calculation, and *n* is the total number of the calculations of the safety coefficient for surface durability of internal gear.

The Figure 1 presents the main effect plot for S/N ratio for safety coefficient for surface durability of internal gear.

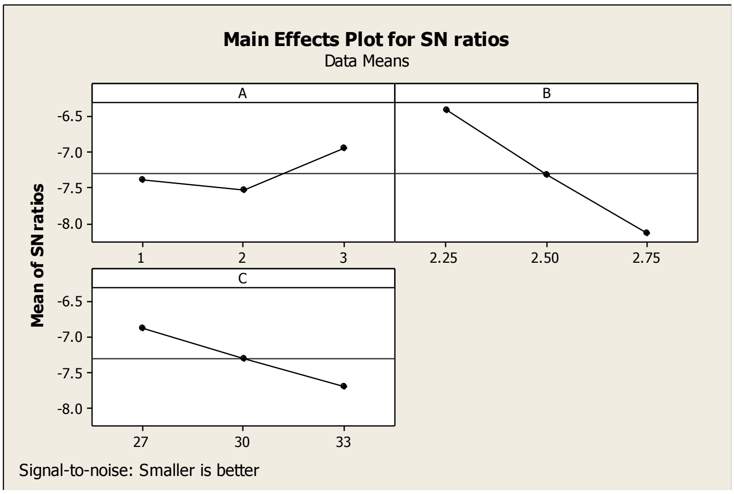

Figure 1. *Main effect plot for S/N ratio for safety coefficient for surface durability of internal gear*

The optimal factor variation is obtained based on the figure 1. The combination of the considered factors, in order to obtain lower values of the safety coefficient for surface durability of internal gear, is A3B1C1. It is noticed that the first factor is on the third level (which means: A3= C15E), while the other two factors are on the first level (which means: B1=2.25 mm; C1=27 mm). So that the minimum value of the safety coefficient for surface durability of internal planetary gear is obtained for these values of the factors.

The experimental results are analysed with the help of MINITAB 16 [10, 11], a statistical analysis software, which is widely used in many fields of engineering research. Results are analysed by ANOVA with a confidence limit of 95% or P-value of 0.05. The results of analysis of variance (ANOVA) are presented in Table 3.

Table 3. *Analysis of Variance for S/N ratios*

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Pr (%)
A	2	1.6204	1.6204	0.81018	7951.40	0.000	8.95
B	2	13.4363	13.4363	6.71817	65934.29	0.000	74.23
C	2	3.0426	3.0426	1.52129	14930.47	0.000	16.81
Residual Error	20	0.0020	0.0020	0.00010			0.01
Total	26	18.1013					100

The last column in the Table 3 shows the percentage effect of all factors on the safety coefficient for surface durability of internal gear. The module with 74.23% has the greatest influence on the value of the safety coefficient for surface durability of internal gear, followed by the gear width with 16.81% and the material with 8.95%. Their error contribution is 0.01%.

4 REGRESSION ANALYSIS

After finding the significant factors, which affect the response, the mathematical equations through regression analysis have been developed using tools of Minitab to estimate the safety coefficient for surface durability of internal planetary gear. Developed regression equation for the safety coefficient for surface durability of internal gear is:

$$S_{Ha} = -0.961111 - 0.0588889 \cdot A + 0.922222 \cdot B + 0.0366667 \cdot C. \quad (2)$$

The course of one variable in relation to another can be monitored and evaluated based on the regression model. It is possible to predict the safety coefficient for surface durability of internal gear for different values of the considered parameters by the mathematical model.

5 ARTIFICIAL NEURAL NETWORK (ANN)

Nowadays, people are striving to reduce the number of experiments, one way is the use of the artificial neural networks. Due to the complexity of neural networks, the softwares are commonly used for their training. In this paper, the networks trained in the software Matlab R2016a [14] are feed forward neural networks. When training networks in software backpropagation algorithm is used. The basic neural network consists of three layers, as follows: input layer, hidden layer and output layer. The input data is obtained by the surrounding environment, the hidden layer is for processing the data, while output layer represents the result obtained by the network training [15,16].

For the purpose of predicting the behaviour of the safety coefficient for surface durability of internal gear, the neural network has been created with three inputs, 10 neurons in the hidden layer, and with one output. The material, module and the gear width are used as the input. The Figure 2 shows the regression coefficient obtained for training, validation and testing of the obtained results, as well as the overall regression coefficient which is 0.98. This shows the exceptionally good correlation between the experimental results (results obtained by the calculation) of the safety coefficient for surface durability of internal gear and the results obtained by the use of neural network.

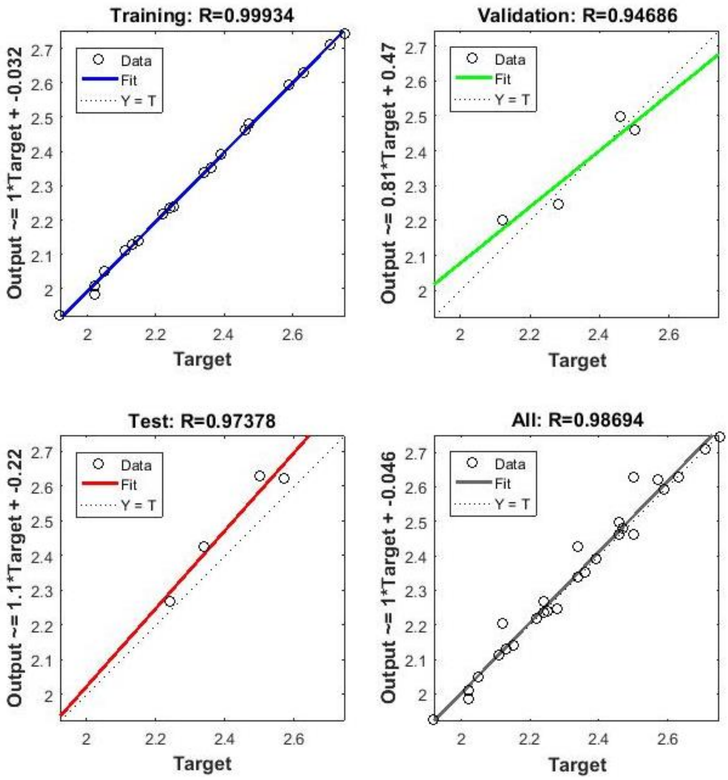

Figure 2. *Regression plot*

The Figure 3 shows the diagram obtained by comparing the experimental results and the results obtained by the Taguchi and ANN methods.

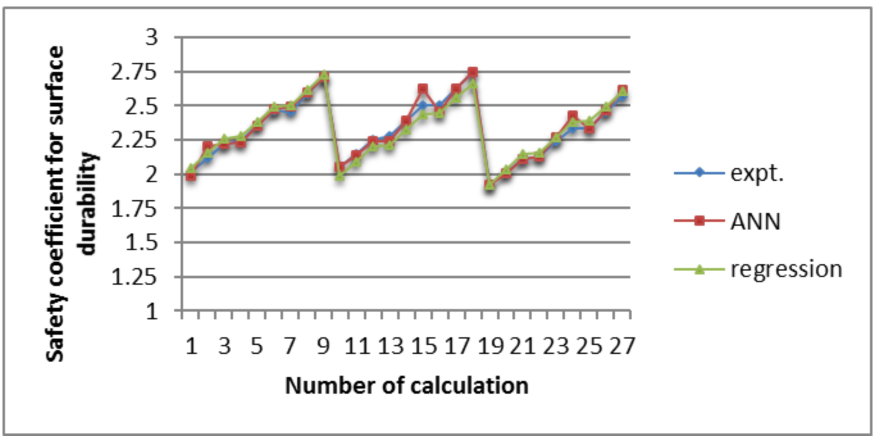

Figure *3. Comparative review of the results*

It is noticed that there is no major deviation of the ANN and regression results from the calculated one, based on the comparative review of the results. However, in this case, the results obtained by the Taguchi method are better than the results obtained by the ANN. With high reliability, the ANN and Taguchi methods can be used to predict the safety coefficient for surface durability of internal gear.

6 CONCLUSION

The calculation of one simple planetary gear was performed in this paper, followed by the optimization of the transmission by using two softwares for the purpose of its comparison. Taguchi and ANN methods are applied in order to reduce the costs and the time of experimentation, and in order to optimize the transmission.

By applying ANOVA analysis, it is noticed that the greatest influence on the safety coefficient for surface durability of internal gear has the module (74.23%), followed by the gear width (16.81%) and the material (8.95%). Besides the influence of each factor individually on the safety coefficient for surface durability of internal gear, the optimal factor variation was determined. The lowest value of the safety coefficient for surface durability of internal gear is to be obtained when applying the material C15E, the module 2.25 mm and the gear width 27 mm.

By comparing the results obtained by the Taguchi and ANN methods, it is noticed that they are quite similar to the experimental results. Although, in this case, the Taguchi method gives the closer results, to the experimental ones, in comparison to the ANN. The results of the applied methods are satisfactory and both methods can be used, with high reliability, for predicting the safety coefficient for surface durability of internal gear.

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NOMENCLATURE

A material,
B module, mm
C gear width, mm
S/N signal-to-noise ratio,
y the safety coefficient for surface durability of internal gear obtained by the calculation,
n the total number of the calculations of the safety coefficient for surface durability of internal gear,
CI confidence interval,
$F_{\alpha:1,V_2}$ Fisher distribution,
V_e pooled error variance,
r number of repeated trials,
n_{eff} number of effective measured results,
$T_{S_{Ha}}$ total mean value of safety coefficient for surface durability of internal gear,
S_{Ha} safety coefficient for surface durability of internal gear,
A3,B1,C1 the S/N response for the main factors at the designated levels,

Greek symbols

α confidence level.

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