APPLICATION OF TAGUCHI METHOD FOR THE SELECTION OF OPTIMAL PARAMETERS OF PLANETARY DRIVING GEAR

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Abstract:
An experimental research is performed in this study in order to optimize the parameters of planetary driving gear. An orthogonal array and analysis of variance (ANOVA) are employed to investigate the factors: material, module and gear width on the safety coefficient for surface durability. Statistical methods of signal to noise ratio and ANOVA with 95% confidence were applied to quantify the effects of considered factors as well as to obtain the minimum value of the safety coefficient for surface durability. The results of this analysis have shown that the gear module with 80.953% has the greatest influence on the safety coefficient for surface durability of the gear. The second influential factor is a gear width with 18.392%. And the material with 0.615% has the least influence on the safety coefficient for surface durability of the gear. The regression analysis is also shown in the study.

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1. INTRODUCTION

Mechanical transmissions are usually components of every machine. The most common mechanical transmissions are mechanical gears. Mechanical gears are machine elements used for motion transmission and torque from one shaft to another. Gearing can be internal and external.

Planetary mechanism is a mechanism where one main part rotates around its axes as well as some other axes and where driving and driven shaft are coaxial. Planetary mechanisms consist of gear transmissions, usually cylindrical ones, which are meshed in various ways. The basic planetary mechanism consists of two concentric gear, satellite and satellite carrier [1].

Planetary gear is a special kind of planetary mechanism where one part is static while two basic parts are connected to driving and driven shaft. Unlike the planetary mechanism which only transmits motion, the planetary gear transmits power, besides the motion.

Planetary gears can be simple and combined. Combined planetary gears are formed by series of simple planetary gears.

Planetary gears are widely used in many applications. They are used with motor vehicles, tool and textile machines, transport devices. Nevertheless, they are even used with helicopters, windmills, clocks, acu-screwdrivers, bicycles, etc. [1,2].

One of the examples of planetary gear usage is Ravigneaux planetary gear, which is used with car automatic transmissions, and its kinematic analysis is given in [3]. Besides Ravigneaux planetary gear there are also other types of planetary gears which are used with automobile automatic transmissions and its systematization is given in [4].

It is possible to make a selection of optimal parameters of planetary driving gear by applying different methods. One of the methods for parameter optimization is Taguchi method. There are a large number of papers for optimization of planetary gears by using this method. P. S. Kamble and V. S. Jadhav have performed the optimization of satellite carrier browning process of planetary gear, velocity, power supply and number of passes by using Taguchi method. The aim of the study was to examine the final condition of the surface and micro-hardness [5]. Sourabh Mandol, Debraj

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Bhattacharjee and Pranab K. Dan have studied a durability prediction of the planetary gear. They used Taguchi method in the study in order to obtain linear regression of a model for predicting a nominal safety coefficient, by which they have indicated a maximum load of planetary gear for input parameters. The aim of using this method for the purpose of optimization is to reduce the failures of planetary gear pairs while performing [6]. Also, Miladinović and Veličković have performed optimization of planetary gear using Taguchi method. The linear regresion using this method was obtained, and comparised with linear regression obtained by Artificial Neural Network. It was concluded that Taguchi method gave better results, in this study, than ANN [7].

Many parameters influence a safety coefficient of planetary gear. Some of those parameters are number of gear teeth, module, gear width and material. Planetary gears with better or worse characteristics can be obtained by variation of these parameters.

The aim of the study is to obtain favourable results which provide opportunity to improve the observed planetary gear. It is necessary to find the most influential factor by using Taguchi methods and ANOVA analysis as well as the optimal variant of considered factors for the purpose of obtaining minimal safety coefficient for surface durability of a driving gear.

2. HISTORICAL DEVELOPMENT OF PLANETARY GEAR

According to available data, the planetary mechanism was used even in ancient China, around 2600 BC. This mechanism was called south-pointing chariot (figure 1.a). This kind of chariot had moving figure at its top with outstretched hand pointing south. The figure was connected to planetary mechanism, and the planetary mechanism was connected to the wheels of the chariot. By turning the wheels, the figure was always pointing toward south by using planetary mechanism [8].

There was no other data about the usage of planetary mechanism until the invention of shipwreck in 1901 near the Greek island Antikythera. The parts of the mechanism were found on this wreck, and the mechanism was named after this island Antikythera mechanism (figure 1.b). It is assumed that this mechanism dates from the First century BC., and that was used to predict the eclipses of the Sun and the Moon, and other astrological phenomena based on Babylonian cycles of arithmetic progression [9,10].

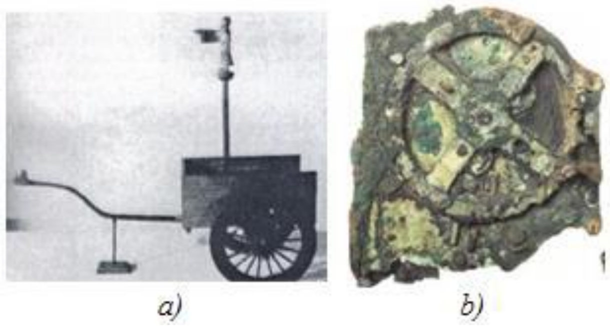

Fig. 1. a) South-pointing chariot [8], **b)** Antikythera mechanism [10]

James Watt had found the way of converting piston reciprocating motion into rotational motion by means of sun-satellite mechanism. This mechanism had allowed flywheel to turn around several times during one toggle tact. Since the toggle was moving slowly, this was a great improvement. The motor, which had been patented in 1782 year by Boulton and Watt (figure 2), had a significant improvement– steam cylinder had used valve above and below the toggle for the purpose of independent connection with boiler or capacitor. It had equalized toggle motion by doing the same job with every movement. Watt had another significant improvement on the motor, so-called parallel motion device by which he had accommodated the oscillating motion of the lever (following the arc) with liner motion the toggle [11].

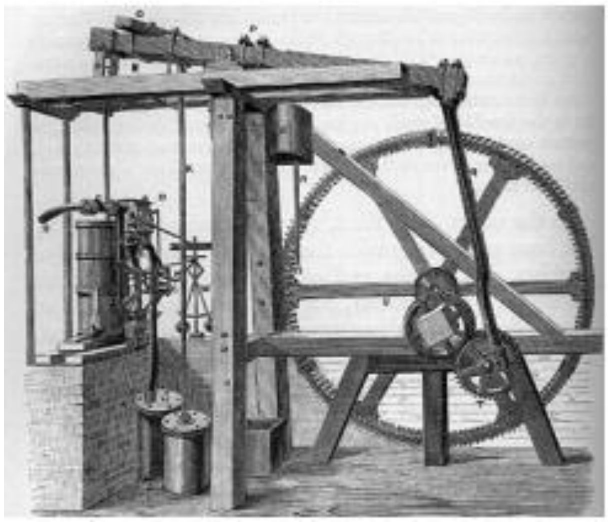

Fig. 2. Watt's steam mechanism [11]

Compactness of planetary mechanism was an advantage with first automobile designers. Dr F. W. Lanchester was first to use the planetary gear with automobiles. After he had placed the gasoline engine into the boat, the next logical step was its usage in inland transportation. Lahchester had designed a vehicle on four wheels, started up by a gasoline engine. He had constructed the engine with two crankshafts and air cooling by using propeller wings which were placed in flywheel. A planetary reducer was used for this vehicle and it had two gears and reverse [12].

3. PLANETARY GEAR CALCULATION

One simple planetary gear is shown in Figure 3. Gear (a) is a central gear or the sun; its axis coincides with mechanism axes and this gear only spins around its own axis; gear (g) is coupled with gear (a) which spins around its axis and with satellite carrier (h) around the axis of central gear (a). Based on this, the gear (g) is called satellite (in foreign literature – planet). Gear (b) is a central gear with inner gearing and it is static. This kind of planetary gear is the gear type A^b_{ha} [12].

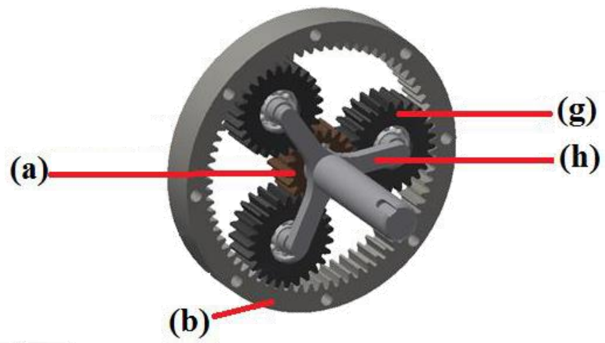

Fig. 3. Planetary gear type A^b_{ha}

A concentration of planetary gear is marked with A, exponent (b) means that this central gear is static, mark (h) in index means that the satellite carrier is an output element, while (a) in index means that the central driving gear is an input element.

The calculation of the gear type A^b_{ha} done according to the standard ISO/DIN 6336/I-IV from 1992 and DIN 3990 from 1992 [13,14]. A detailed calculation is given in [15].

Starting data are shown in the (table 1), where the working machine is a lathe machine, while the driving machine is an electromotor.

The number of teeth: of central driving gear (a) Z_a=20, satellite (g) Z_g=25 and gear (b) Z_b=70 are obtained by the calculation of planetary gear.

A design of the experiment can be set up by the performed calculation of planetary gear. It is possible to optimize the factor by using selected factors and chosen matrix in order to obtain satisfactory value for the safety coefficient for surface durability of a gear.

Table 1. Input data of planetary gear

Input data	Mark	Units	Value
Input power	P	kW	15
Revolution per minute (rpm)	n	min^{-1}	1000
Transfer ratio	i	/	4.5
Life-time	Lh	h	16000

4. EXPERIMENTAL DESIGN

4.1 Taguchi Method

Taguchi method is a robust statistical method that allows independent estimation of the response with minimal number of experiments. This technique helps studying the influence of many factors on the desired and therefore more economic quality characteristic. The best combination of the factors can be determined by studying the influence of some factors on the result. Taguchi method is one of the solutions to that kind of problem. Likewise, it allows experimenting in limited number and predicting the remaining combination of factors [16].

4.2 Material

Materials 16MnCr5 and 28Cr4 are used in this study and they are used for manufacture of gear for planetary gear and they also represent one of the considered factors. By applying Taguchi method and using ANOVA analysis, it is necessary to find an optimal variant of the factors, respectively, appropriate material, as well as optimal values of the remaining considered factors.

4.3 Orthogonal Array L18

Taguchi technique is a very effective tool for process that works consistently and optimally under different conditions of projecting. This method is an experimental design technique, which is useful in reducing the number of experiments by using orthogonal arrays [16]. The influence factors, without its interaction on the safety coefficient for surface durability of a driving gear, are studied in this paper. The code and levels of control parameters are shown in (table 2). In order to set up the experimental design, following factors are selected: material (A), module (B) and gear width (C) and its levels. The first factor is on two levels and the second and third factor has three levels each.

The aim of the experimental plan is to search the most influential factors and optimal factor combination in order to obtain the minimum of safety coefficient for surface durability. Taguchi's L18 orthogonal array was used in the design of experiments and it is shown in (table 3).

Table 2. Levels for various control factors

Control factors	Units	Level I	Level II	Level III
A: Material	/	1 – 16MnCr5	2 – 28Cr4	
B: Module	mm	2.25	2.5	2.75
C: Gear width	mm	27	30	33

Table 3. Experimental design using L18 orthogonal array

L18	A - Material	B – Module	C –Gear width	*SHa* - safety coefficient for surface durability	S/N ratio of the safety coefficient for surface durability
1	1	2.25	27	1.12	-0.98436
2	1	2.25	30	1.18	-1.43764
3	1	2.25	33	1.23	-1.79810
4	1	2.50	27	1.24	-1.86843
5	1	2.50	30	1.31	-2.34543
6	1	2.50	33	1.37	-2.73441
7	1	2.75	27	1.37	-2.73441
8	1	2.75	30	1.44	-3.16725
9	1	2.75	33	1.51	-3.57954
10	2	2.25	27	1.14	-1.13810
11	2	2.25	30	1.19	-1.51094
12	2	2.25	33	1.25	-1.93820
13	2	2.50	27	1.26	-2.00741
14	2	2.50	30	1.33	-2.47703
15	2	2.50	33	1.39	-2.86030
16	2	2.75	27	1.39	-2.86030
17	2	2.75	30	1.46	-3.28706
18	2	2.75	33	1.53	-3.69383

5. RESULTS AND DISCUSSION

(S/N) ratio is the ratio of the mean (signal) to the standard deviation (noise). Regardless of the quality characteristics category, the higher ratio corresponds to better quality characteristics. The method of calculating the (S/N) ratio depends at each run of the experiment on whether the quality characteristic is lower-the-better, higher-the-better, or nominal-the-better [17].

In the present study, (S/N) ratio is calculated as the logarithmic transformation of the loss function by using smaller-the-better criterion as minimum values of the safety coefficient for surface durability by using software Minitab 16. The equation for smaller-the-better characteristic is as follows:

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

where:

(y) is the observed data (safety coefficient for surface durability) and n is the number of observations. The above (S/N) ratio transformation is suitable for minimization of the safety coefficient for surface durability.

5.1 (S/N) Ratio Analysis

Only the main effects of a factor are considered in the present study for it is assumed that interactions of factor effect are negligible. The safety coefficient for surface durability of the first gear (driving gear) is analyse din planetary gear type A^{b}_{ha}. The aim is to obtain its minimum value by using smaller-the-better (S/N) quality characteristic. The effect of considered factors on the safety coefficient for surface durability *SHa* can be determined based on performed Taguchi analysis, as shown in (table 3). Based on factor ranking in (table 4), it can be seen that the module has the greatest influence, followed by gear width and the material. The (figure 4) shows the effect of the considered factors on the safety coefficient for surface durability of a driving gear. The analysis of the experimental results based on (S/N) ratios provides the optimal factor levels. Based on (figure 4), it is concluded that the optimal factor combination is (A1B1C1). So therefore, these factor values get minimum value of the safety coefficient for surface durability of a gear.

Table 4. Response Table for Signal to Noise Ratios for *SHa*

Level	A	B	C
1	-2.294	-1.468	-1.932
2	-2.419	-2.382	-2.371
3		-3.220	-2.767
Delta	0.125	1.753	0.835
Rank	3	1	2

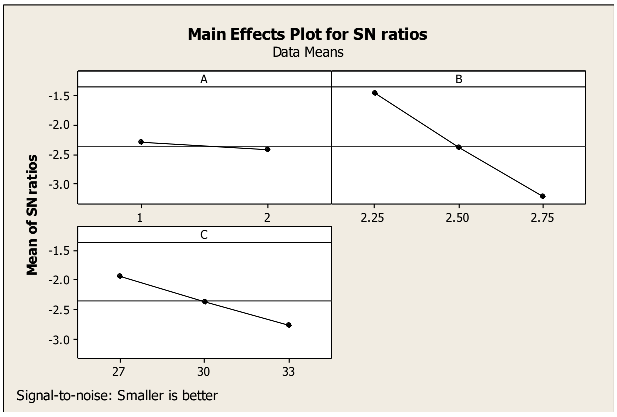

Fig. 4. Main Effects Plot for the safety coefficient for surface durability

5.2 Analysis of Variance (ANOVA)

ANOVA is one of the most commonly used tools when it comes to statistical methods. The results of the (S/N) analysis were used for realization of ANOVA, allowing defining which factor and level influences the final results of experiments. Therefore, ANOVA analysis is used to find factors that are statistically significant and to find optimal factor levels [18-20].

The analysis of experimental data in this study is performed by using powerful tool of Taguchi analysis variance in order to determine factor effects that affect the safety coefficient for surface durability of a gear. The results of ANOVA analysis for the safety coefficient for surface durability of a planetary driving gear are shown in (table 5).

Table 5. Analysis of Variance for *SHa*

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Pr
A	1	0.0701	0.07014	0.07014	188.31	0.000	0.615
B	2	9.2196	9.21963	4.60981	12377.14	0.000	80.953
C	2	2.0946	2.09460	1.04730	2811.95	0.000	18.392
Residual Error	12	0.0045	0.00447	0.00037			0.04
Total	17	11.3888					

This analysis is performed at a 95% confidence level. The parameter is highly statistically significant when the appropriate P value is less than 0.05. The last column in the (table 4) shows percentage effect of (Pr) each factor on the safety coefficient for surface durability of a gear. Based on the performed ANOVA analysis, it can be concluded that the greatest influence on the safety coefficient for surface durability of a gear has the module with 80.953%, followed by the gear width with 18.392% and material at the end with 0.615%. The factor interactions are not considered in this analysis for it is assumed to be statistically irrelevant. Based on P value, it can be concluded that all considered factors are statistically significant for considered safety coefficient for surface durability of a planetary driving gear.

5.3 Regression Analysis

Regression Analysis model is made up by using the (S/N) ratio value. This kind of analysis gives the result which determines whether the factors are significantly in relation with data response i.e. the safety coefficient for surface durability of a gear and relative significance of each factor in the model.

The equation of regression for the safety coefficient for surface durability of a planetary gear is as follows:

$$SHa = -0.669+0.0189A+0.530B+0.0211C \quad (2)$$

The coefficients of the equation of regression are shown in (table 6).

Table 6. Coefficients of regression analysis

Term	Coef.	SE Coef.	T	P
Constant	-0.669444	0.0259455	-25.8019	0.000
A	0.018889	0.0029472	6.4091	0.000
B	0.530000	0.007212	73.4157	0.000
C	0.021111	0.0006016	35.0918	0.000

The model of linear regression was obtained through statistic software (MINITAB 16) [18,21].

Coefficient sequence by absolute value points out the significance of each factor in the response: the factor with highest coefficient has the greatest influence. Based on the (table 6), it can be concluded that the greatest influence has the module, followed by the gear width and material, at the end.

Linear regression line obtained on the base of experimental results of the safety coefficient for surface durability is given in (figure 5).

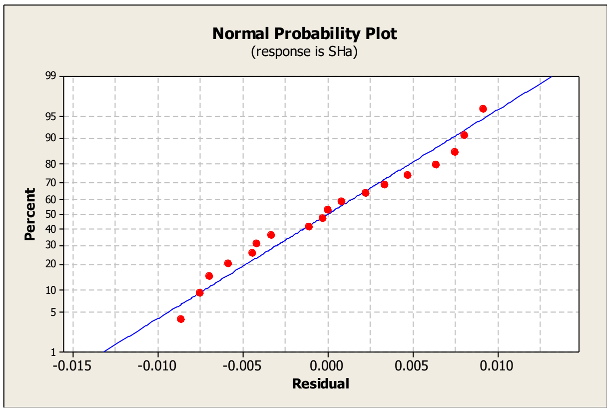

Fig. 5. Normal probability plot for the safety coefficient for surface durability

Normal probability plot represents the comparison between the actual experimental results and the predicted values. The model given in the equation (2) corresponds to the diagram in (figure 5).

Table 7 shows the comparison of estimated experimental values and results obtained by regression analysis for the safety coefficient for surface durability of a driving gear. The experiment is performed for optimal variant of factors (A1B1C1).

Table 7. Results for the optimal combination of factors for *SHa*

	Optimal parameter combination		
	Prediction	Experimental	Regression
A1B1C1	1.11167	1.12	1.1119446
S/N ratio(db)	-0.98018	-0.98436	-0.921663

6. CONCLUSION

The experimental optimization of planetary driving gear is used in this study in order to reduce the safety coefficient for surface durability of a gear tooth by using Taguchi method.

Based on Taguchi and ANOVA analysis, it is concluded that the greatest influence on the safety coefficient for surface durability of a driving gear has the gear module with 80.953%, while the least influence has the gear material with 0.615%. The C factor or the gear width is also statistically significant for the safety coefficient for surface durability of a driving gear tooth with 18.392%.

The optimal variant of the factor (A1B1C1) is obtained by the experimental research. The optimization of driving gear factors has shown that all the factors are on the first level, which means that the material is (16MnCr5), the module is 2.25 mm and the gear width is 27 mm.

Performed regression analysis provides factor variance with monitoring the values for the safety coefficient for surface durability of a gear and, thereby, the quality characteristic is predicted in chosen range of considered factors.

REFERENCES

[1] B. Stojanović, M. Blagojević, Mechanical Transmitters, Faculty of Engineering University of Kragujevac, Kragujevac, 2015.

[2] S. Kuzmanović, Machine elements, FTN publishing, Novi Sad, 2010.

[3] M. Novaković, B. Stojanović, M. Milisavljević, S. Miladinović, The kinematic analysis of Ravigneaux planetary gear set; Technical Diagnostics, 15(1), 2016: pp.7-12.

[4] S. Ilić, B. Stojanović, Systematization of planetary gear set configurations which are implemented in automatic transmissions; Technical Diagnostics, 14(4), 2015: pp.21-26.

[5] P. S. Kamble, V. S. Jadhav, Experimental study of Roller burnishing process on plain carrier of planetary type gear box; International Journal of Modern Engineering Research (IJMER), 2(5), 2012: pp.3379-3383.

[6] S. Mandol, D. Bhattacharjee, D. K. Pranab, Robust optimization in determining failure criteria of a planetary gear assembly considering fatigue condition; Industrial application, Structural and Multidisciplinary Optimization, 53(2), 2016: pp.291-302.

[7] S. Miladinović, S. Veličković, Optimization and prediction of safety coefficient for surface durability of planetary gearbox using Taguchi design and Artificial Neural Network, 3rd International Scientific Conference COMETa 2016, 2016, Jahorina, B&H, RS, pp.139-146.

[8] F. Dainian, R. S. Cohen, Chinese Studies in the History and Philosophy of Science and Technology, volume 179, Boston Studies in the Philosophy and History of Science, Kluwer academic publishers, The Netherlands, 1996.

[9] T. Freeth, Y. Bitsakis, X. Moussas, J. H. Seiradakis, A. Tselikas, H. Magou, M. Zafeiropoulou, R. Hadland, D. Bate, A. Ramsey, M. Allen, A. Crawley, P. Hockley, T. Malzbender, D. Gelb, W. Ambrisco, M. G. Edmunds, Decoding the ancient Greek astronomical calculator known as the Antikythera Mechanism, Nature, 444 (7119), 2006: pp.587-591.

[10] M. T. Wright, The Antikythera Mechanism and the early history of the moon-phase display; Antiquarian Horology, 29(3), 2006: pp.319-329.

[11] M. Abrams, James Watt Biography; ASME. https://www.asme.org/engineering-topics/articles/energy/james-watt (accessed 15.04.2016).

[12] R. August, R. Kasuba, J.L. Frater, A. Pintz, Dynamics of Planetary Gear Trains, NASA Contractor, Cleveland State University Clevel and Ohio, 1984.

[13] V. Nikolić, Machine elements, Faculty of Mechanical Engineering, Kragujevac, 2004.

[14] S. Tanasijević, A. Vulić, Mechanical Transmitters - planetary gears and variators, Faculty of Mechanical Engineering, Kragujevac, 2006.

[15] S. Miladinović, The optimal selection parameters of gear pairs of planetary gear (Master thesis), Faculty of Engineering University of Kragujevac, Kragujevac, 2014.

[16] B. Stojanović, M. Babić, S. Veličković, J. Blagojević, Optimization of wear behaviour in aluminium hybride composites using Taguchi method, 14th International Conference on Tribology SERBIATRIB '15, 2015, Belgrade, Serbia, pp.81-89.

[17] B. Stojanović, M. Babić, S. Veličković, J. Blagojević, Tribological behavior of aluminum hybrid composites studied by application of factorial techniques; Tribology Transactions, 59(3), 2016: pp.522-529.

[18] S. Veličković, S. Analysis of influential factors on the tensile strength of polyethylene using the factorial design; Technical Diagnostics, 14(3), 2015: pp.33-40.

[19] S. Veličković, B. Stojanović, M. Babić, I. Bobić, Optimization of tribological properties of aluminum hybrid composites using Taguchi design; Journal of composite materials, 0(0), 2016: pp.1-11.

[20] B. Stojanović, M. Babić, L. Ivanović, Taguchi optimization of tribological properties of Al/SiC/Graphite composite; Journal of the Balkan Tribological association, 22(3), 2016: pp.2582-2595.

[21] B. Stojanovic, S. Velickovic, J. Blagojevic, D. Catic, Statistical analysis of roughness timing belt in operation using full factorial methods; Journal of the Balkan Tribological Association, 21(3), 2015: pp.514-524.