IETI Transactions on Engineering Research and Practice
http://ieti.net/TERP/

2018, Volume 2, Issue 2, 34-41, DOI 10.6723/TERP.201812_2(2).0005

OPTIMIZATION OF RAVIGNEAUX PLANETARY GEAR SET

Slavica Miladinovic[1, a], Sandra Veličković[1,b] , Blaža Stojanović [1,c], Stefan Milojević[1,d]
[1]Faculty of Engineering University of Kragujevac, Serbia
[a]slavicam@kg.ac.rs, [b]sandrav@kg.ac.rs, [c] blaza@kg.ac.rs, [d]stefanmilojevic94@hotmail.com

Abstract The advancement of the automotive industry tended to replace classical gears with fixed axes, with planetary gear set with movable axes. Planetary gear sets have many advantages over classical gears, but their design is more complex. One of the planetary gear sets, which is highly applicable in the automotive industry, is the Ravigneaux planetary gear set. This planetary gear set consists of gears with external and internal toothing, which for different cases of movement of gears provides different output speeds and torques. The optimization of the module and the gear width of the the Ravigneaux gear set in order to reduce its mass, and taking into account the values of the safety coefficient, was carried out in this paper. Observed optimization factors are: three materials (37Cr4, Ck15 and 15CrNi6), three modules (1mm, 1.25 mm and 1.5 mm) and three gear widths (20 mm, 22 mm and 25 mm).These values satisfy the conditions of the planetary gear kinematics. By optimizing the Ravigneaux planetary gear set saving of the mass of around 28% was achieved.

Keywords: Optimization; planetary gears; Ravigneaux planetary gear set; safety coefficient.

1. INTRODUCTION

Transmissions are necessary part of every machine in the industry. The advancement of technology tends to reduce the losses as well as the mass of the gear set, but the transmission structure is becoming more complex. Nowadays planetary gear transmissions are widely used. The increased use of planetary gear set is because of the advantages that this type of gear set brings into the machine systems in which it is built, which are: large transmission ratios, the possibility of sharing power on the drive shaft to a multiple driven shafts and vice versa, the possibility of achieving different transmission ratios, compactness and other.

These gears, as already said, can achieve large transmission ratios, but it should be noted that this reduces the efficiency. The possibility that the space between the central gears is filled with more satellites ensures good use of the interior space and allows a compact construction of planetary gears. The use of multiple satellites allows the load to be transmitted simultaneously with a large number of teeth, which leads to a reduction in load and selection of smaller modules.Thanks to these features, planetary gears are two to three times lighter than conventional gear sets of the same power and transmission ratio. Equitable mass reduction requirements and dimensional dimensions correspond to drives with planetary gear units.

Although planetary gears have a number of advantages, they, also, have important shortcomings: more complicated than conventional gears, they have complex kinematics, they are sensitive to the change in distance between axes, additional forces may occur due to the insufficient accuracy of the load distribution between satellites,require high accuracy in construction and assembly, as this can also contribute additional loads on gears.

2018, Volume 2, Issue 2, 34-41, DOI 10.6723/TERP.201812_2(2).0005

There is a lot of types of planetary gears. The simplest planetary gear consists of two central gears and one row of satellites [1].

One type of planetary gear that is the subject of numerous research is Ravigneaux's planetary gear set that arose as a result of the improvement of previous gear sets, such as Simpson (patented in 1944). Ravigneaux's planetary gear set is a double planetary gear patented by Paul Ravigneaux in 1949 in France. It consists of two central gears with an external toothing and one central gear with internal toothing, between which there are two satellites connected by one carrier [2-5].

In this paper, based on the calculation of the complete Ravigneaux's planetary gear set in the Autodesk Inventor 2016 software given in [6], optimization of the obtained safety coefficient for surface durability for one gear pair was performed. Optimizing first gear pair of Ravigneaux's planetary gear set is affecting the whole gear set in terms of its dimensions and mass.

The implementation of experiments can not be imagined today without applying some of the optimization methods. Among a lot of optimization methods widely used are Taguchi method and Artificial Neural Network (ANN).

Taguchi method is an optimization method consisting of a limited number of experiments. Within this method there are two tools used: the orthogonal array and the S/N ratio that allow the function to be optimized within the experiment limits. Optimization methods are used to reduce the number of experiments and thus save time and expenses necessary for conducting of experiments [7]. In [8] performed design optimization of planetary gear combining Taguchi method and Computer Aided Engineering. Taguchi method was used for obtaining a linear regression model in order to predict a nominal safety factor value. Regression model for prediction of safety coefficient was based on the simulation data obtained from ANSYS software. The conclution that was drawn from this paper was that this kind of approacch can be used for optimisation of the system with certainty that the component will perform with efficiency under assigned conditions. Another optimization of planetary gear with the help of Taguchi method was performed by S. Miladinovic et.al. in [9]. They investigated influence of material, module and gear width on the safety coefficient for surface durability by varying two types of material, three modules and three gear widths. This optimization gave the best combination of factors, and has shown that the most influential factor was module. Combination of Taguchi method and ANN for optimization of safety coefficient for surface durability of internal gear of planetary gear set was used in [10]. Influence of module, material and gear width was investigated. With the help of ANOVA analysis it was found that most influential was module, than gear width and the least influential was material. ANN was used for prediction of safety coefficient for surface durability of internal gear of planetary gear set.

In this paper, the Taguchi method was used to determine the percentage influence of the factors considered as well as to determine the optimal level of factors for the safety coefficient for surface durability of gear pair of Ravigneaux planetary gear set (in the text below safety coefficient), while the ANN method was used to predict the values of safety coefficient.

IETI Transactions on Engineering Research and Practice
http://ieti.net/TERP/
2018, Volume 2, Issue 2, 34-41, DOI 10.6723/TERP.201812_2(2).0005

2. DESIGN OF EXPERIMENTS USING TAGUCHI METHODOLOGY

Taguchi method was developed by Dr. Genichi Taguchi in the 1980s and represents a statistical method of quality engineering. This method is a method of experimental design that attempts to minimize the variability of products and processes by selecting the best combination of level of factors that can be controlled using orthogonal arrays. This method's approach is a very useful for determining the best combination of different factors for an objective function [7].

In the last few years, this efficient and systematic way of optimizing design for performance, quality and expences has been used for numerical and theoretical research.

In this study, for the optimization of the level of safety coefficient of planetary gear, an analysis of the material, the module and the gear width was performed. Due to the complexity of this type of planetary gear set in this paper, optimization for one pair of gears was made more precisely for the pair a-g (Figure 1).

Table 1 shows the factors and their levels used to optimize the safety coefficient.

Table 1. Levels for various control factors.

Factor	Units	Level 1	Level 2	Level 3
(A) Material	/	37Cr4	Ck15	15CrNi6
(B) Gear width	mm	20	22	25
(C) Module	mm	1	1.25	1.5

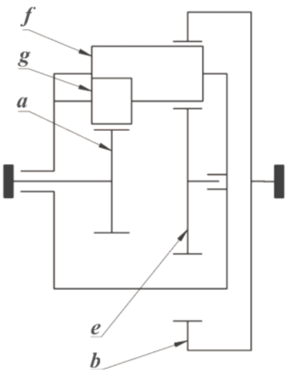

Figure 1. Scheme of Ravigneaux planetary gear set, a- first central gear, g, f – satellites, e - second central gear, b - third central gear.

Using the Taguchi technique and using the ANOVA analysis, the influence of the considered factors on the safety coefficient of the Ravigneaux planetary gear is found. Orthogonal arrays, in the Taguchi method, are used to design the experiments. In this case, the orthogonal array L27 was selected for the experiment plan (Table 2). The safety coefficients of the Ravigneaux planetary gear set are obtained in the Autodesk Inventor software and are shown in Table 2. These results are transformed into signal-to-noise ratio which is a measure of quality characteristics deviating from the desired values. Different quality characteristics may be chosen, depending on the experimental objective. In the Taguchi methodology, the quality of any particular design solution is quantified using a ratio. Three different S/N ratios can be used for the calculations, i.e., the smaller is better, the higher is better and nominal is better [8]. In this study, because minimum safety coefficient is the objective function, the smaller is better situation has been selected. The S/N ratio of the-smaller the better can be expressed as follows [11, 12]:

IETI Transactions on Engineering Research and Practice
http://ieti.net/TERP/

2018, Volume 2, Issue 2, 34-41, DOI 10.6723/TERP.201812_2(2).0005

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

wherein n is the number of repetitions of the experiment and yi is the average measured value of experimental data i. Unit of S/N ratio is decibel (dB). S/N ratio is used to select the optimum levels of parameters based on the minimum deviation. The optimal is the combination of factors that has the highest S/N ratio.

Table 2. Safety coefficient and S/N ratios for the L27 orthogonal array.

	Material	Gear width	Module	SHa – safety coefficient	S/N ratio of the safety coefficient	ANN
1	37Cr4	20	1.00	1.000	0.00000	1.000
2	37Cr4	20	1.25	1.259	-2.00051	1.339
3	37Cr4	20	1.50	1.533	-3.71084	1.648
4	37Cr4	22	1.00	1.021	-0.18051	1.021
5	37Cr4	22	1.25	1.312	-2.35868	1.312
6	37Cr4	22	1.50	1.601	-4.08783	1.601
7	37Cr4	25	1.00	1.065	-0.54699	1.059
8	37Cr4	25	1.25	1.399	-2.91635	1.399
9	37Cr4	25	1.50	1.696	-4.58852	1.696
10	Ck 15	20	1.00	1.060	-0.50612	1.026
11	Ck 15	20	1.25	1.351	-2.61311	1.351
12	Ck 15	20	1.50	1.644	-4.31804	1.699
13	Ck 15	22	1.00	1.097	-0.80413	1.097
14	Ck 15	22	1.25	1.408	-2.97205	1.408
15	Ck 15	22	1.50	1.717	-4.69541	1.717
16	Ck 15	25	1.00	1.144	-1.16852	1.213
17	Ck 15	25	1.25	1.501	-3.52761	1.501
18	Ck 15	25	1.50	1.819	-5.19665	1.819
19	15CrNi6	20	1.00	1.112	-0.92210	1.112
20	15CrNi6	20	1.25	1.418	-3.03352	1.418
21	15CrNi6	20	1.50	1.725	-4.73578	1.725
22	15CrNi6	22	1.00	1.151	-1.22151	1.229
23	15CrNi6	22	1.25	1.478	-3.39349	1.446
24	15CrNi6	22	1.50	1.802	-5.11510	1.802
25	15CrNi6	25	1.00	1.201	-1.59086	1.201
26	15CrNi6	25	1.25	1575	-3.94561	1.575
27	15CrNi6	25	1.50	1.909	-5.61612	1.909

The calculation of the S/N ratio (Signal to Noise Ratio) with the use of equation 1 depends on the results obtained by the experiments. By analyzing the S/N ratio, the optimal level of each factor can be determined along with an optimized set of factors.

Then, an optimal combination of factors that can affect the degree of security can be predicted. In Table 3, are shown values for S/N ratio "Smaller is better" and Figure 2 shows the Main Effects Plot for the safety coefficient.

Table 3. Response Table for Signal to Noise Ratios "Smaller is better".

Level	Material	Gear width	Module
1	-2.2656	-2.4267	-0.7712
2	-2.8668	-2.7587	-2.9734
3	-3.2860	-3.2330	-4.6738
Delta	1.0204	0.8064	3.9026
Rank	2	3	1

2018, Volume 2, Issue 2, 34-41, DOI 10.6723/TERP.201812_2(2).0005

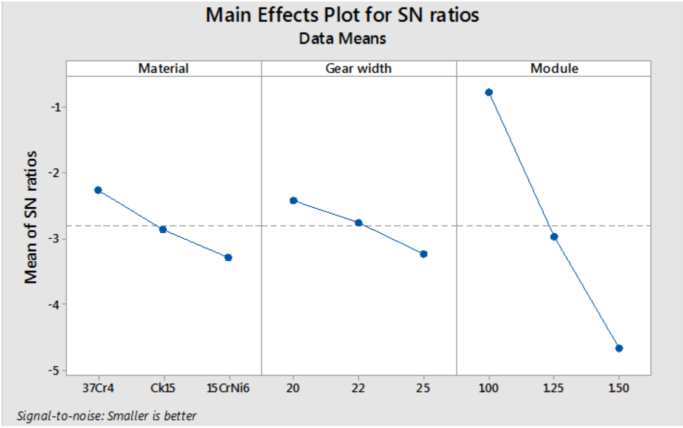

Figure 2. Main Effects Plot for the safety coefficient.

The optimal combination of the factors considered is A1B1C1, while the influence of each factor individually cannot be determined by the S/N ratio, and for that ANOVA analysis is used. For determining influence of significant process factors the statistical method called Analysis of Variance (ANOVA) was used [8, 13]. ANOVA is used for finding how much the contribution of the most influential factor has changed in the generated design. The results presented in Table 4 show that all factors are primary factors because the p-value is less than 0.05.

Table 4. Analysis of Variance for S/N ratios of the safety coefficient.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Pr %
Material	2	4.7355	4.7355	2.3677	566.77	0.000	6.17
Gear width	2	2.9563	2.9563	1.4781	353.83	0.000	3.85
Module	2	68.9147	68.9147	34.4573	8248.13	0.000	89.86
Residual Error	20	0.0836	0.0836	0.0042			0.11
`Total	26	76.6900					100.00
DF - degree of freedom, Seq SS - Sequential sum of squares, Adj SS - Adjusted sum of squares,Adj MS - Adjusted mean square, F – value, Pr percentage of contribution							

According to ANOVA, the most important and influential factor on the safety coefficients of planetary gear set, for 95% confidence level, is the module with 89.86%, followed by the material with 6.17% and the gear width with 3.85% influence.

Figure 3 shows the 2d contour plot of material and module dependency on safety coefficients of planetary gear set.

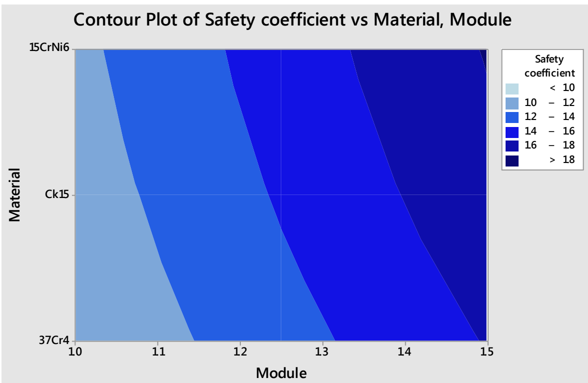

Figure 3. Contour plot of safety coefficient dependance of material and module.

2018, Volume 2, Issue 2, 34-41, DOI 10.6723/TERP.201812_2(2).0005

3. ARTIFICIAL NEURAL NETWORKS

For reducing of number of experiments, also, can be used ANN. ANN is artificial intelligence system inspired by information processing of a human brain. It is a system which consists of number of interconnected neurons. Each neuron has memory where are stored information that are processed. Simple neural network consists of three layers: input layer, hidden layer and output layer [12, 14, 15]. ANNs are not programed they are trained, and for that have been designed training algorithms; the mostly used is back-propagation Levenberg–Marquardt algorithm, which was used in this paper. ANN with 3 input factors, one hidden layer, with 15 neurons, and one output was developed for predicting safety coefficient (Figure 4). As transfer function was used log-sigmoid (logsig) transfer function. ANN output is given in Table 2, and regression diagram which shows regression coefficients for training, validation, testing and overall is shown on Figure 5.

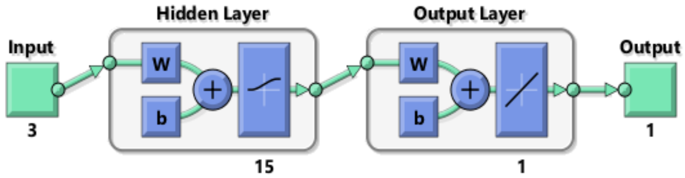

Figure 4. Shematic representation of developed ANN.

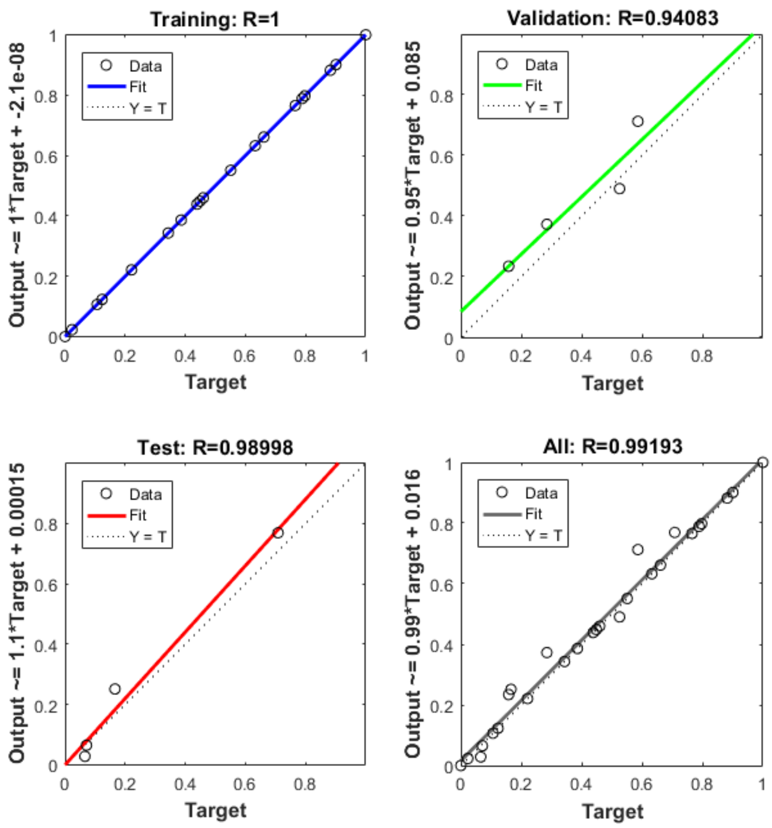

Figure 5. Regresion diagram obtained for trained network.

It can be noticed that overall regression coefficient is 0.99 which shows very good corelation between experimental results and ANN's output.

2018, Volume 2, Issue 2, 34-41, DOI 10.6723/TERP.201812_2(2).0005

4. CONCLUSION

Optimization of one gear pair of Ravigneaux planetary gear set was performed in this paper in order to notice the behaviour of safety coefficient when material, module and gear width are changed. Based on Taguchi and ANOVA analysis, it is concluded that the greatest influence on the safety coefficient has module with 89.86%, while the least influence has the gear width with 3.85%. The optimal variant of the factors (A1B1C1) is obtained by the Taguchi method. The optimization of safety coefficient has shown that all the factors are on the first level, which means that the material is 37Cr4, the module is 1 mm and the gear width is 20 mm. The ANN model was, also, developed with regression coefficient of 0.99 which means that this model can be used for prediction of safety coefficient with great reliability. Difference in the mass between Ravigneaux planetary gear set with max and min value of safety coefficient is 4.921 kg which is around 28% of mass of whole gear set.

Acknowledgements

This paper presents the results obtained during research within the framework of the project TR 35021, supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia.

References

[1] Tanasijevic S., and Vulic A., 2006, *Mechanical transmissions: Planetary gears and Variators*, Faculty od Mechanical Engineering, Kragujevac.
[2] Novaković M., Stojanović B., Milosavljević M., and Miladinović S., 2016, The kinematic analysis of Ravigneaux planetary gear set, *Technical Diagnostic*, Vol.15, no.1, p.p. 7-12.
[3] https://patents.google.com/patent/US2518824A/, accesed 31.05.2018.
[4] https://patents.google.com/patent/US2631476A/en, accesed 31.05.2018.
[5] http://carpedia.club/view/5855, accesed 31.05.2018.
[6] Milojević S., 2018, Calculation and construction of Ravigneaux planetary gear set, Master thesis, Faculty of Engineering University of Kragujevac, Serbia.
[7] Taguchi G., 1993,*Taguchi on Robust Technology Development: Bringing Quality Engineering Upstream*. ASME Press, New York.
[8] Mandol S., Bhattacharjee D., and Dan P. K., 2016, Robust optimization in determining failure criteria of a planetary gear assembly considering fatigue condition, *Structural and Multidisciplinary Optimization*, Vol. 53, no. 2, p.p. 291-302.
[9] Miladinović S., Veličković S., and Novaković M., 2016, Application of Tagouchi method for the selection of optimal parameters of planetary driving gear, *Applied Engineering Letters*, Vol. 1, no. 4, p.p. 98-104.
[10] Miladinović S., and Veličković S., 2016, Optimization and prediction of safety coefficient for surface durability of planetary gearbox using Taguchi design and Artificial Neural Network, *3 rd INTERNATIONAL SCIENTIFIC CONFERENCE COMETa 2016*, Jahorina, B&H, RS, p.p. 139-146.
[11] Kim H.K., Jeon J.Y., Park J.Y., Yoon S., and Na S., 2010, Noise reduction of a high-speed printing system using optimized gears based on Taguchi's method, *Journal of Mechanical Science and Technology*, Vol. 24, no. 12, p.p. 2383-2393.
[12] Stojanovic B., Blagojević J., Babic M., Veličković S., and Miladinovic S., 2017, Optimization of hybrid aluminum composites wear using Taguchi method and artificial neural network, *Industrial Lubrication and Tribology*, Vol. 69, no 6, p.p. 1005-1015.
[13] Wei F., and Lin H., 2011, Multi-objective optimization of process parameters for the helical gear precision forging by using Taguchi method, *Journal of Mechanical Science and Technology*, Vol. 25, no. 6, p.p.1519-1527.

2018, Volume 2, Issue 2, 34-41, DOI 10.6723/TERP.201812_2(2).0005

[14] Miladinovic S., Rankovic V., Babic M., Stojanovic B., and Velickovic S., 2017, Prediction of tribological behavior of aluminium matrix hybrid composites using artificial neural networks, *15th International Conference on Tribology – Serbiatrib '17*, p.p. 142-149, Kragujevac.
[15] Stojanović B., Venc A., Bobić I., Miladinović S., and Skerlić J., 2018, Experimental optimisation of the tribological behaviour of Al/SiC/Gr hybrid composites based on Taguchi's method and artificial neural network, *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, Vol. 40, no. 311, p.p. 1-14.