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Optimal Safe Factor for Surface Durability of First Central and Satellite Gear Pair in Ravigneaux Planetary Gear Set

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Abstract

Ravigneaux planetary gear sets provide great amount of tooth contact resulting reduction of safety coefficient for surface durability (SCSD). Because, they carry huge torque distributing load evenly among multiple satellite gears. They are being used widely in many passenger car vehicles. This article deals with optimal input variables such as gear material, gear width and module for the minimum SCSD of the first central gear pair in Ravigneaux planetary gear set. Modified Taguchi approach is followed to carry out the above task. Empirical relation is developed for SCSD in terms of the input variables. Taguchi's L9 orthogonal array is well suited for the 3 levels of 3 input variables. In this process, minimum number of test data is considered to construct ANOVA table for assessing the contribution of the input variables on the overall SCSD value. Estimated range of SCSD is presented for all combinations of the input variables and their levels. Test data is found to be close to/within the estimated range.

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Keywords; *Gear width; Gear material (37Cr4, CK15 and 15CrNi6); Module; Planetary gearbox; Safety coefficient; Taguchi approach.*

I. INTRODUCTION

Introduction of planetary gears influence advancement in automotive transmission systems. Compared to conventional gear sets, planetary gear sets lead in torque multiplication, speed reduction, high torque to weight ratio and low back lash at less compact size with high efficiency. In 1949 Ravigneaux has introduced a double planetary gear set with a single planet carrier using multiple satellites allowing load transmission simultaneously with a large number of teeth, which leads to load reduction and accommodates smaller modules [1]. Ravigneaux planetary gear set includes a ring gear, one small and large sun gears, three short and long pinions or satellites with a single planet carrier. The smaller sun gear mesh with three short planetary pinion gears which acts as idler gears to drive the three long planetary pinions gears. Figure-1 shows the larger planetary pinion gears mesh with the large sun gear and ring gear. By using multiple satellite gear pairs, Ravigneaux gear set results in safety coefficient reduction and more resistance to damage due to evenly distributed loads.

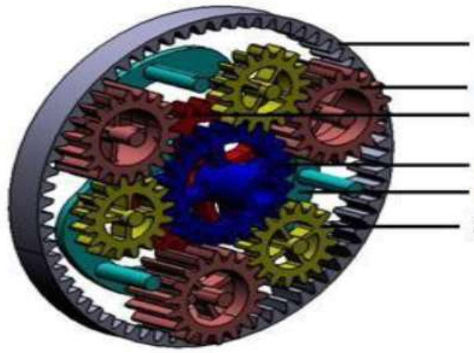

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Figure-1: Ravigneaux planetary gear set [1].

Miladinović et al. [2] have considered the first central and satellite gear pair in Ravigneaux planetary gear set to examine the influence of gear material, gear width, and module in safety coefficient for the surface durability (SCSD). They have used Taguchi's *L*27 orthogonal array with signal-to-noise (S/N) ratio transformation and ANN (Artificial neural network). Asimple efficient statistical Taguchi approach is being utilized for solving several industrial/engineering optimization problems [3-12]. A modified Taguchi method is introduced to have the range of the output responses and their optimal solution by converting multi-objective output responses to a simple single-objective function [13-16]. This paper adopts modified Taguchi method considering *L*9 orthogonal array for tracing optimal parameters to achieve minimum SCSD. An empirical relation for SCSD of internal planetary gear is presented in terms of gear material, gear width, and module. Results are within the range of estimation.

II. DATA ACQUISITION

Miladinović et al. [2] have analyzed the complete Ravigneaux planetary gear set (see Figure-2) adopting the 2016 version of the Autodesk Inventor software [17]. Three levels are assigned for three parameters viz., module, gear width, and gear material while performing the gear optimization. *L*27 Orthogonal array is considered which accommodates all level combinations of the parameters. ANN is applied to assess the SCSD of the first central pair of Ravigneaux planetary gear set, which controls the design. In the present study, Taguchi's *L*9 Orthogonal array is considered and developed an empirical relation for the SCSD in terms of the parameters viz., module, gear width, and gear material. Range of SCSD is presented for all level combinations of parameters utilizing the modified Taguchi approach. The optimal parameters are obtained using the Taguchi's simple single-objective optimization technique.

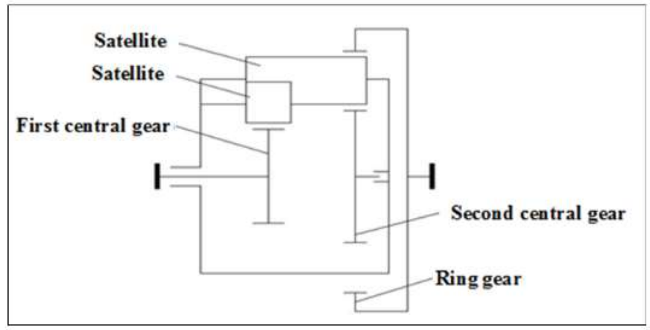

Figure- 2: A schematic representation of Ravigneaux planetary gear set [2].

III. ANALYSIS OF VARIANCE (ANOVA)

For the 3 levels of 3 parameters (viz., module, gear width, and gear material), Taguchi approach recommends *L*9 orthogonal array. Modified Taguchi method recommends accommodation of another parameter naming the fictitious or dummy parameter for the same number of experiments. The 3 parameters viz., gear material, module and gear width are referred by the letters A, B and C respectively. The dummy or fictitious parameter is referred by the letter D with 3 assigned levels (d1, d2, and d3). Table-1 gives 3 input variables and 1 dummy variable with 3 levels. Table-2 provides SCSD for the assigned levels of the input variables in each test run of the *L*9orthogonal array.

Table-1: Input variables and their levels for the SCSD of the first central pair of Ravigneaux planetary gear set.

Input variables	Designation	Level-1	Level-2	Level-3
Gear material	A	37Cr4	Ck15	15CrNi6
Gear width (mm)	B	20	22	25
Module (mm)	C	1.00	1.25	1.50
Fictitious or Dummy	D	d_1	d_2	d_3

Table-2: SCSD of the first central pair of Ravigneaux planetary gear set for the assigned levels of the input variables.

Test run	Levels of the input variables				Safety coefficient for surface durability (SCSD)					
					Ref. [2]	Eq. (2)	Relative Error (%)	Eq. (1)	Range of estimation	
	A	B	C	D					From	To
1	1	1	1	1	1.000	0.977	2.28	1.000	0.963	1.000
2	1	2	2	2	1.312	1.326	-1.08	1.312	1.312	1.349
3	1	3	3	3	1.696	1.705	-0.50	1.696	1.690	1.727
4	2	1	2	3	1.351	1.360	-0.63	1.351	1.345	1.382
5	2	2	3	1	1.717	1.694	1.33	1.717	1.680	1.717
6	2	3	1	2	1.144	1.158	-1.24	1.144	1.144	1.181
7	3	1	3	2	1.725	1.739	-0.82	1.725	1.725	1.762
8	3	2	1	3	1.151	1.160	-0.74	1.151	1.145	1.182
9	3	3	2	1	1.575	1.552	1.45	1.575	1.538	1.575

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ANOVA is done to know the significance of input variables on SCSD. From ANOVA Table-3, the gear material (A), gear width (B), module (C) and fictitious parameter (D) have 5.3, 3.2, 91.1 and 0.4% contributions on the overall SCSD with zero Error (%). The 0.4% contribution of D is nothing but the Error (%) on SCSD. The bold values marked in Table-3 are the lowest mean values corresponding to the input variables. The levels of those input variables provide minimum SCSD. In the present study, the set of optimal input variables for minimum SCSD are A1B1C1, in which subscripts are the levels. The identified optimal parameters to achieve minimum SCSD are: gear material, A1 =37Cr4; gear width, B1 =1 mm; and module, C1

=20 mm. For these optimal input variables (A1B1C1), the reported value of SCSD of internal planetary gear in Table-2 is 1.

Table-3: ANOVA for SCSD of internal planetary gear

Input variable	SCSD (Safety coefficient for surface durability)			SOS (Sum of Squares)	%Contribution
	1-Mean	2-Mean	3-Mean		
A	**1.336**	1.404	1.484	0.033	5.3
B	**1.359**	1.393	1.472	0.020	3.2
C	**1.098**	1.413	1.713	0.566	91.1
D	1.431	1.394	1.399	0.002	0.4
			Total	0.621	100

IV. SCSD ESTIMATES

Using the mean values of ANOVA Table-3 in the additive law [18], it is possible to estimate SCSD for any set of input variables within the assigned levels. That means, one can determine SCSD for all level combinations of input variables (27 cases). It should be noted that the mean values of SCSD in ANOVA Table-3 are generated from the 9 test runs, which provides the data of 27 test runs. The details of estimating SCSD are presented below.

Denoting the SCSD by a mathematical symbol (φ), one can estimate □ □ e □ from the mean values of ANOVA Table-3 for a set of input variables (A, B, C, D) using the additive law (a simplesuperposition model) as [18]

$$\varphi e = \varphi(Ai, Bj, Ck, Dl) = \varphi mean + \Delta\bar{\varphi}Ai + \Delta\bar{\varphi}Bj + \Delta\bar{\varphi}Ck + \Delta\bar{\varphi}Dl$$

$$= \varphi mean + (\bar{\varphi}Ai - \varphi mean) + (\bar{\varphi}Bj - \varphi mean) + (\bar{\varphi}Ck - \varphi mean) + (\bar{\varphi}Dl - \varphi mean)$$

$$= \bar{\varphi}\,Ai + \bar{\varphi}\,Bj + \bar{\varphi}\,Ck + \bar{\varphi}\,Dl - 3\varphi mean \forall i,j,k,l=1,2,3 \quad (1)$$

Here $\varphi mean$ is the grand mean; φ_{Ai}, φ_{Bj}, φ_{Ck}, and φ_{Dl} are the mean values of φ for i, j, k and l levels of input variables A, B, C, and D respectively. In the present study, $\varphi mean$=1.408.

Estimates of φ for the input variables (A , B ,C) can be found from

$$\varphi = \varphi(Ai, Bj, Ck) = \bar{\varphi}Ai + \bar{\varphi}Bj + \bar{\varphi}Ck - 2\varphi mean,$$

$\bar{\varphi}_D - \varphi_{mean}$, which is considered as the correction to equation (2).

For the selected optimal input variables (viz., gear material, A_1 =37Cr4; gear width, B_1 =1 mm; and module, C_1 =20 mm), one can find SCSD from equation (2) as

$$\varphi_e = (A_1, B_1, C_1) = \bar{\varphi}_{A1} + \bar{\varphi}_{B1} + \bar{\varphi}_{C1} - 2\varphi_{mean} = 1.336 + 1.359 + 1.098 - 2*1.408 = 0.977$$

The set of optimal input variables (A_1, B_1, C_1) are found in test run-1 of Table-2. The correction to equation (2) could be one of the following:

$\Delta\bar{\varphi}_{D1} = \bar{\varphi}_{D1} - \varphi_{mean}$=1.431 – 1.408=0.023;

$\Delta\bar{\varphi}_{D2} = \bar{\varphi}_{D2} - \varphi_{mean}$ =1.394 – 1.408= -0.014; and

$\Delta\bar{\varphi}_{D3} = \bar{\varphi}_{D3} - \varphi_{mean}$ =1.399 – 1.408= -0.009.

These corrections are applied to the above estimated SCSD value of 0.977. One can find three

estimates of $\varphi e$for the optimal input variables (A_1, B_1, C_1) as 1, 0.963 and 0.968. The estimatedrange

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of φe from these values is from 0.963 to 1, whereas the reported value [2] of 1 close to that of the upper bound value. The range of φe can be obtained from equation (2) applying the minimum and maximum correction values of -0.014 and 0.023 respectively. Table-4 presents estimates of SCSD for all 27 combinations of input variables. The test data [2] is close to the estimates (see Figure-3) as well as within/close to the estimated range. Figure-4 shows a good comparison of ANN predictions [2] with the present estimates of SCSD using equation (2).

Table-4: SCSD estimates for all 27 possible combinations of the 3 levels for 3 input variables (viz., gear material (A), gear width (B) and module (C)).

S. No.	Levels of input variables			Safety coefficient of surface durability (SCSD)					
	A	B	C	Ref. [2]	ANN [2]	Eq. (2)	Relative Error (%)	Estimated range	
								From	To
1	1	1	1	1.000	1.000	0.977	2.28	0.963	1.000
2	1	1	2	1.259	1.339	1.292	-2.59	1.277	1.314
3	1	1	3	1.533	1.648	1.592	-3.82	1.577	1.614
4	1	2	1	1.021	1.021	1.012	0.89	0.998	1.035
5	1	2	2	1.312	1.312	1.326	-1.08	1.312	1.349
6	1	2	3	1.601	1.601	1.626	-1.58	1.612	1.649
7	1	3	1	1.065	1.059	1.090	-2.37	1.076	1.113
8	1	3	2	1.399	1.399	1.405	-0.40	1.390	1.427
9	1	3	3	1.696	1.696	1.705	-0.50	1.690	1.727
10	2	1	1	1.060	1.026	1.045	1.39	1.031	1.068
11	2	1	2	1.351	1.351	1.360	-0.63	1.345	1.382
12	2	1	3	1.644	1.699	1.660	-0.95	1.645	1.682
13	2	2	1	1.097	1.097	1.080	1.56	1.066	1.103
14	2	2	2	1.408	1.408	1.394	0.98	1.380	1.417
15	2	2	3	1.717	1.717	1.694	1.33	1.680	1.717
16	2	3	1	1.144	1.213	1.158	-1.24	1.144	1.181
17	2	3	2	1.501	1.501	1.473	1.90	1.458	1.495
18	2	3	3	1.819	1.819	1.773	2.55	1.758	1.795
19	3	1	1	1.112	1.112	1.125	-1.16	1.111	1.148
20	3	1	2	1.418	1.418	1.439	-1.50	1.425	1.462
21	3	1	3	1.725	1.725	1.739	-0.82	1.725	1.762
22	3	2	1	1.151	1.229	1.160	-0.74	1.145	1.182
23	3	2	2	1.478	1.446	1.474	0.28	1.460	1.497
24	3	2	3	1.802	1.802	1.774	1.56	1.760	1.797
25	3	3	1	1.201	1.201	1.238	-3.07	1.224	1.261
26	3	3	2	1.575	1.575	1.552	1.45	1.538	1.575
27	3	3	3	1.909	1.909	1.852	2.97	1.838	1.875

Figure-3: Comparison of SCSD estimates using equation (2) with test data [2]

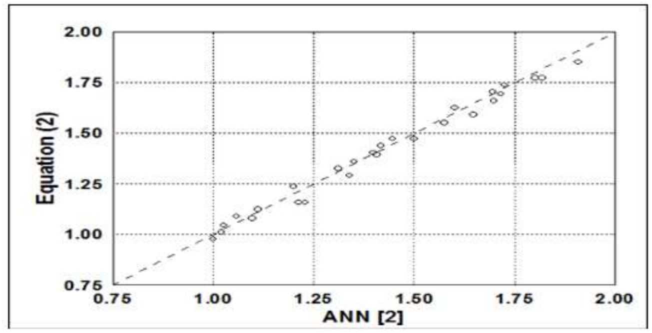
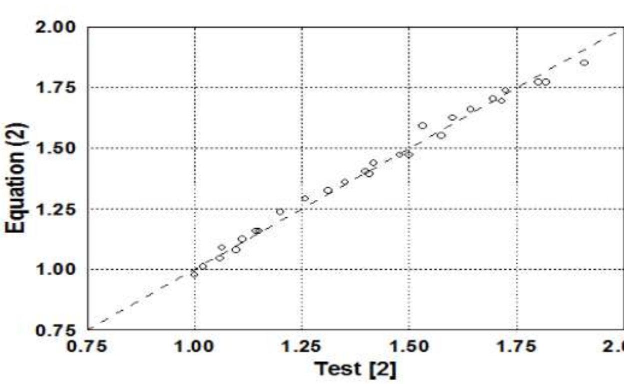


Figure-4: Comparison of SCSD estimates using equation (2) with ANN predictions [2]



V. DEVELOPMENT OF EMPIRICAL RELATION

From ANOVA Table-3, one can represent the φ_A data in a second-order polynomial of A; the φ_B data in a quadratic polynomial of B; and the φ_C data in a quadratic polynomial of C. From equation (2), one can find a quadratic relation for SCSD: $\varphi_e = \varphi_A + \varphi_B + \varphi_C - 2\varphi_{mean}$ in terms of the 3 input variables A, B and C. When an input variable is not a number, it can be represented ina coded form as follows. The levels of input variable A are gear materials.Hence, φ_A isrepresented by a second-order polynomial function of ξ_1 by defining $\xi_1 = -1$, for the gearmaterial, A_1= 37Cr4; $\xi_1 = 0$, for the gear material, A_2= Ck15; $\xi_1 = 1$, for the gear material, A_3=

[illegible] and φ as a second-order polynomial functions of [illegible]

respectively. Thus, using the ANOVA Table-3 and the additive law (2), an empirical relation for SCSD is arrived as

$$SCSD = 1.594222 + 0.075854\xi_1 + 0.005855\xi_1^2 + 0.0505\xi_2 + 0.021834\xi_2^2 + 0.307107\xi_3 - 0.00717\xi_3^2 \quad (3)$$

Table-5 gives SCSD values from equation (3) for the 27 test runs. Minimum and maximum corrections are applied to the determined SCSD and found the estimated range. Most of the SCSD values

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of Ref. [2] are found to be close to/within the estimated range. RSM (response surface methodology) provides a truly quadratic model having cross-terms, whereas such termsare missing in the Empirical relation (3). Because, the three mean functions φ_A, φ_B and φ_C expressed independently as a second-order polynomial functions of ξ_1, ξ_2 and ξ_3 respectively.Mean value plots confirm these quadratic functions. Figure-5 shows the equivalence of results from equations (2) and (3). For the specified gear material and gear width, SCSD value increases with increasing module (see Figure-6).

Table-5: Determination of SCSD from the empirical relation (3) for all 27 possible combinations of the 3 levels for 3 input variables (viz., gear material (A), gear width (B) and module (C)).

S. No.	Parameters			Safety coefficient (SC)					
	Gear material (A)	Gear width, B (mm)	Module, C (mm)	Ref. [2]	ANN [2]	Eq. (3)	Relative Error (%)	Estimated range From	To
1	37Cr4	20	1.00	1.000	1.000	0.977	2.28	0.963	1.000
2	37Cr4	20	1.25	1.259	1.339	1.292	-2.59	1.277	1.314
3	37Cr4	20	1.50	1.533	1.648	1.592	-3.82	1.577	1.614
4	37Cr4	22	1.00	1.021	1.021	1.012	0.89	0.998	1.035
5	37Cr4	22	1.25	1.312	1.312	1.326	-1.08	1.312	1.349
6	37Cr4	22	1.50	1.601	1.601	1.626	-1.57	1.612	1.649
7	37Cr4	25	1.00	1.065	1.059	1.090	-2.37	1.076	1.113
8	37Cr4	25	1.25	1.399	1.399	1.405	-0.40	1.390	1.427
9	37Cr4	25	1.50	1.696	1.696	1.705	-0.50	1.690	1.727
10	Ck15	20	1.00	1.060	1.026	1.045	1.39	1.031	1.068
11	Ck15	20	1.25	1.351	1.351	1.360	-0.63	1.345	1.382
12	Ck15	20	1.50	1.644	1.699	1.660	-0.95	1.645	1.682
13	Ck15	22	1.00	1.097	1.097	1.080	1.56	1.066	1.103
14	Ck15	22	1.25	1.408	1.408	1.394	0.98	1.380	1.417
15	Ck15	22	1.50	1.717	1.717	1.694	1.33	1.680	1.717
16	Ck15	25	1.00	1.144	1.213	1.158	-1.24	1.144	1.181
17	Ck15	25	1.25	1.501	1.501	1.473	1.90	1.458	1.495
18	Ck15	25	1.50	1.819	1.819	1.773	2.55	1.758	1.795
19	15CrNi6	20	1.00	1.112	1.112	1.125	-1.16	1.111	1.148
20	15CrNi6	20	1.25	1.418	1.418	1.439	-1.50	1.425	1.462
21	15CrNi6	20	1.50	1.725	1.725	1.739	-0.82	1.725	1.762
22	15CrNi6	22	1.00	1.151	1.229	1.160	-0.74	1.145	1.182
23	15CrNi6	22	1.25	1.478	1.446	1.474	0.28	1.460	1.497
24	15CrNi6	22	1.50	1.802	1.802	1.774	1.56	1.760	1.797
25	15CrNi6	25	1.00	1.201	1.201	1.238	-3.07	1.224	1.261
26	15CrNi6	25	1.25	1.575	1.575	1.552	1.45	1.538	1.575
27	15CrNi6	25	1.50	1.909	1.909	1.852	2.97	1.838	1.875

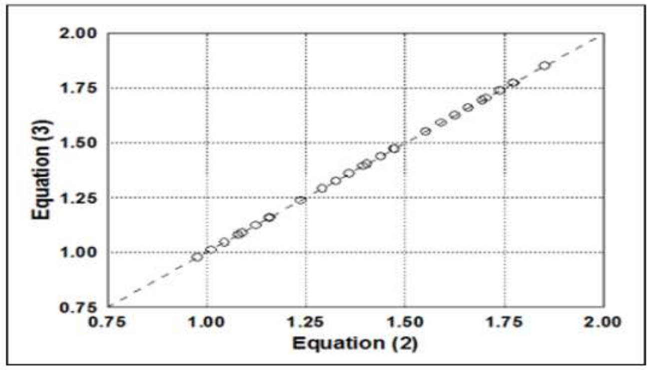

Figure- 5: Comparison of SCSD estimates using equations (2) and (3).

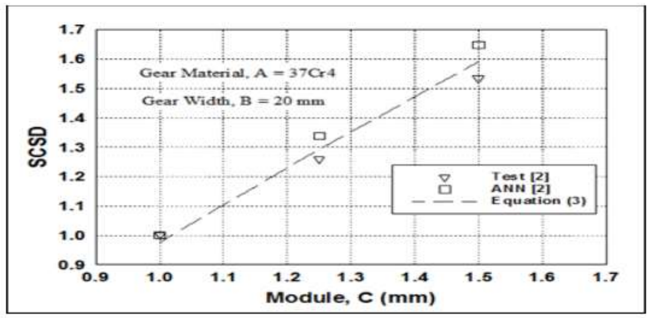

Figure-6: Variation of SCSD with module, C for gear material, A=37Cr4 and gear width, B= 20 mm.

Industries generally adopt simple and reliable approaches to tackle optimization problems. The S/N ratio transformation in the Taguchi method may be required for conversion of repeated experimental data in to a single objective value [16]. Sonawane et al. [19] have made a review on GRA (grey relational analysis) [20-25], GA (genetic algorithm) [26, 27], TLBA (teacher learning base algorithm) [28], RSM (response surface methodology) [29] and PSO (particle swarm optimization) [30]. None of them have indicated the drawbacks in the simple Taguchi method. Miladinović et al. [2] have considered the full factorial design of 27 experimental data for ANN predictions and also applied S/N ratio transformation in the Taguchi method, whereas the present analysis considers only 9 experiments and presented the estimated range of SCSD for the 27 experiments. This study confirms the adequacy of the modified Taguchi approach and suggests

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avoiding the application of S/N ratio transformation, when repeated experimentation is not planned.

VI. CONCLUDING REMARKS

This study deals with the identification of optimal input variables viz., gear material, gear width and module to achieve minimum safety coefficient for surface durability (SCSD) considering the first central and satellite gear pair of Ravigneaux planetary gearbox. Modified Taguchi method is adopted to estimate the range of SCSD for the specified set of input variables. Empirical relation is developed and validated for SCSD in terms of gear material, module and gear width. The present analysis considers only 9 experiments and presents the estimated range of SCSD for the 27 experiments. The estimated data can be utilized for ANN predictions.

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