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Parameters Identification and Minimization of Safety Coefficient for Surface Durability of Internal Planetary Gear Using the Modified Taguchi Approach

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Abstract

Planetary gear systems produce a large amount of torque with speed reduction creating large contact area between the gears and more resistant to damage due to evenly distributed load. They are being used extensively in gearhead motors, turbine engines, tractors and construction equipment, automatic transmissions, and electric screwdrivers. Many researchers have obtained optimal solution using Taguchi technique and adopting S/N ratio transformation, which is recommended to represent the scatter in output responses of repeated trial runs. If fact, Taguchi method suggests the additive law considering ANOVA table mean values relevant to the optimal input variables while estimating the deterministic output response. In this article, modified Taguchi approach is adopted for selecting optimal parameters viz., gear material, module and gear width to minimize the safety coefficient for surface durability (SCSD) of internal planetary gear. Also, the SCSD range is estimated for the desired set of input parameters. The developed empirical relation for SCSD is validated considering all possible combinations of the input parameters.

Keywords; *Gear width; Gear material (16MnCr5, 28Cr4 and C15E); Module; Planetary gearbox; Safety coefficient; Taguchi approach*

I. INTRODUCTION

Gear boxes are the most common mechanical transmission. Starting from horseless carriage gear box in 1904 by Sturtevant brothers to the automatic transmissions, the gear boxes have got a key development introducing planetary gears. Since the movement of the gearbox members resembles the movement of planets around the sun, they are named as the planetary gears. A planetary gear set consists of a sun gear, planet gears, and a ring gear (see Figure-1). The sun gear at the center transmits torque to the planet gears, which gears orbit around the sun gear and mesh with an outer ring gear. Planetary gear systems produce a large amount of torque with speed reduction. They create large contact area between the gears, which are more resistant to damage due to evenly distributed load. They are widely used in automatic transmissions, electric screwdrivers, turbine engines, gearhead motors, tractors and construction equipment.

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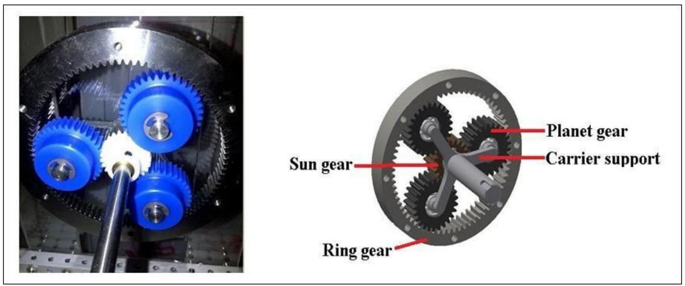

Figure-1: A planetary gear set [3]

Planetary gears have formed the subject by a fairly large number of theoretical and experimental investigations. Marinović et al. [1] have performed the optimization of a simple planetary gear from the results by changing the number of gear teeth, module, number of satellites and gear width. Mandol et al. [2] have applied Taguchi method and adopted a linear regression model for safety factor prediction of the planetary gear. Miladinović and Veličković[3] have examined the influence of gear material, gear width, and the module on the safety coefficient for the surface durability (SCSD) of the internal gear of the planetary gearbox using Taguchi's L_{27} orthogonal array and adopting the S/N ratio transformation (which is recommended only for the output responses of repeated trial runs). They have applied ANN (Artificial neural network) to predict SCSD of the internal planetary gear.

Several industrial/engineering optimization problems [4-12] are solved using a systematic statistical Taguchi approach. This paper considers only the Taguchi's L_9 orthogonal array to get optimal solution by identifying a set of input parameters for the minimum SCSD of internal planetary gear. Following the modified Taguchi approach [12-15], the valid SCSD range is obtained for all combinations of the input variables (viz., gear material, gear width, and the module). The developed empirical relation for the SCSD of internal planetary gear is validated for all possible combinations of input parameters.

II. DATA ACQUISITION

Miladinović and Veličković [3] have analyzed the A_{ha}^{b} planetary gearbox, whose schematic representation is shown in Figure-2. A_{ha}^{b} indicates the transmission with one-sided satellite. 'b' represents immovable (fixed) member, 'h' is a driven member (output) transferring the large torsion moment, and 'a' is the drive member (input). They have obtained: 3 number of satellites; a total transmission ratio of 4.5; and the number of teeth of gear with internal gearing is 70.

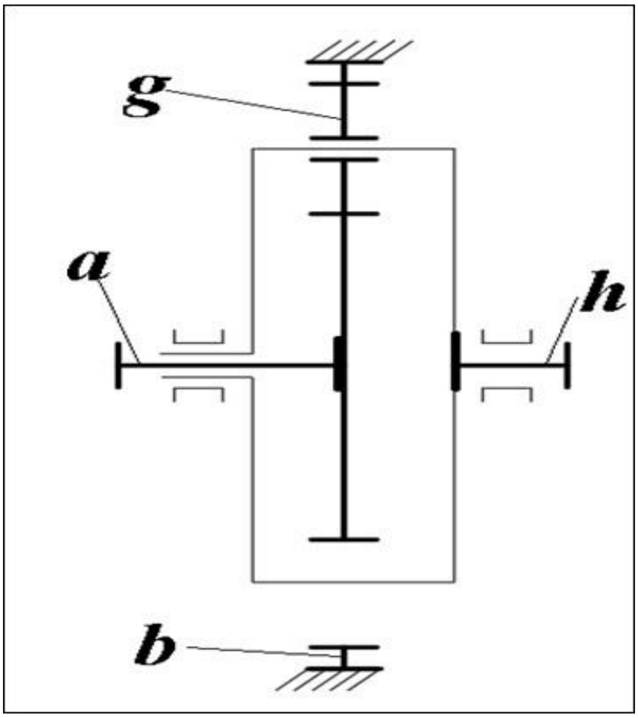

Figure- 2: Schematic representation of A_{ha}^{b} planetary gearbox [3]

The gear optimization is performed assigning 3 levels to the 3 parameters (viz., module, gear width, and gear material). The surface durability safe factor calculations are done according to the BS-ISO-6336-2 standards and using MIT CALC program of epicyclic gearing for the L_{27} orthogonal array (i.e. the full factorial design of experiments). ANN is applied to estimate the SCSD of internal gear of planetary gearbox. In the present analysis, the modified Taguchi approach [12-15] is followed by considering Taguchi'sL_9 orthogonal array and established an empirical relation for the SCSD in terms of 3 parameters. Single-objective optimization technique of Taguchi is very simple and sufficient for tracing the optimal parameters.

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III. ANALYSIS OF VARIANCE (ANOVA)

The 3 parameters viz., gear material, module and gear width are designated respectively by A, B and C to have easy reference. As in [12], a fictitious parameter (D) is accommodated in Table-1. Table-2 gives the SCSD of internal planetary gear for the set of input variables as per the Taguchi's L_9 orthogonal array. ANOVA results in Table-3 indicate 9.112, 73.733 and 17.14% contributions of the gear material (A), module (B) and gear width (C) respectively, whereas the 0.015% contribution of D is nothing but the error in the total variation of the safety coefficient. For minimum safety coefficient marked bold values in Table-3 are $A_3B_1C_1$ (denoting the subscripts as the level of the parameter). Hence, the optimal parameters for the minimum safety coefficient are: gear material, A_3 =C15E; module, B_1 =2.25 mm; and gear width, C_1 =27 mm. The safety coefficient is 1.92 for surface durability of internal planetary gear corresponding to the optimal parameters ($A_3B_1C_1$).

Table-1: Input parameters including fictitious and their 3 levels

Parameters	Designation	Level-1	Level-2	Level-3
Gear material	A	16MnCr5	28Cr4	C15E
Module (mm)	B	2.25	2.50	2.75
Gear width (mm)	C	27	30	33
Fictitious	D	d_1	d_2	d_3

Table-2: Safety coefficient for surface durability (SCSD) for the level of parameters in 9 test runs following Taguchi approach.

Test run	Levels of parameters				Safety coefficient for surface durability (SCSD)					
					Ref. [3]	Eq. (2)	Error (%)	Eq. (1)	Estimated range	
	A	B	C	D					Minimum	Maximum
1	1	1	1	1	2.02	2.020	0.0	2.02	2.017	2.023
2	1	2	2	2	2.36	2.363	-0.1	2.36	2.360	2.367
3	1	3	3	3	2.71	2.707	0.1	2.71	2.703	2.710
4	2	1	2	3	2.15	2.147	0.2	2.15	2.143	2.150
5	2	2	3	1	2.50	2.500	0.0	2.50	2.497	2.503
6	2	3	1	2	2.50	2.503	-0.1	2.50	2.500	2.507
7	3	1	3	2	2.11	2.113	-0.2	2.11	2.110	2.117
8	3	2	1	3	2.13	2.127	0.2	2.13	2.123	2.130
9	3	3	2	1	2.46	2.460	0.0	2.46	2.457	2.463

Table-3: ANOVA for safety coefficient of surface durability (SCSD) of internal planetary gear

Parameter	Safety coefficient of surface durability			Sum of Squares (SOS)	%Contribution
	1-Mean	2-Mean	3-Mean		
A	2.363	2.383	**2.233**	3.9800E-02	9.112
B	**2.093**	2.330	2.557	3.2207E-01	73.733
C	**2.217**	2.323	2.440	7.4867E-02	17.140
D	2.327	2.323	2.330	6.6667E-05	0.015
			Total	4.3680E-01	100

IV. ESTIMATES FROM ANOVA RESULTS

Assuming φ as the safety coefficient for surface durability (SCSD), a simple superposition (additive) model [16] is adopted to determine φ from the mean values of SCSD in Table-3 for the specified levels of the input variables A_i, B_j, C_k and D_l (levels i, j, k, l = 1, 2, 3) from

$$\begin{aligned}\varphi_e = \varphi(A_i, B_j, C_k, D_l) &= \varphi_{mean} + \Delta\bar{\varphi}_{Ai} + \Delta\bar{\varphi}_{Bj} + \Delta\bar{\varphi}_{Ck} \\ &= \varphi_{mean} + (\bar{\varphi}_{Ai} - \varphi_{mean}) + (\bar{\varphi}_{Bj} - \varphi_{mean}) \\ &\quad + (\bar{\varphi}_{Ck} - \varphi_{mean}) + (\bar{\varphi}_{Dl} - \varphi_{mean}) \\ &= \bar{\varphi}_{Ai} + \bar{\varphi}_{Bj} + \bar{\varphi}_{Ck} + \bar{\varphi}_{Dl} - 3\varphi_{mean} \qquad (1)\end{aligned}$$

$\forall i, j, k, l$ = 1, 2, 3.

Here φ_e is the estimate of the SCSD; φ_{mean} is the mean of φ for the 9 test runs; $\bar{\varphi}_{Ai}$ is the mean value of φ to level 'i' of the input parameter A. The mean value $\bar{\varphi}_{Bj}$ is for the level 'j' of the input parameter B. The mean value $\bar{\varphi}_{Ck}$ is for the level 'k' of the input parameter C. The mean value $\bar{\varphi}_{Dl}$ is for the level 'l' of the input parameter D. The mean value of SCSD from 9 test runs, φ_{mean} =2.327. It should be noted that equation (1) determines the SCSD for any combination of the assigned levels of the input variables A_i, B_j, C_k and D_l (levels i, j, k, l = 1, 2, 3). Values of φ_e from equation (1) consider the contribution of the fictitious parameter. For the specified levels of input variables A_i, B_j and C_k, one can find φ_e from

$$\varphi_e = \varphi(A_i, B_j, C_k) = \bar{\varphi}_{Ai} + \bar{\varphi}_{Bj} + \bar{\varphi}_{Ck} - 2\varphi_{mean}, \quad (2)$$

$\forall\, i, j, k$ = 1, 2, 3.

Subtracting (2) from (1), one can get the deviation in the result of equation (2) due to fictitious parameter: $\Delta\varphi_{Dl} = \bar{\varphi}_{Dl} - \varphi_{mean}$.

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Results of equation (1) in Table-2 are very close to the analysis results of Ref. [3], the deviation due to fictitious parameter can become correction to those obtained from equation (2).

The minimum SCSD is possible for the parameters: gear material, A_3 =C15E; module, B_1 =2.25 mm; and gear width, C_1 =27 mm, which can be obtained from equation (2) as

$$\varphi_e = \varphi(A_3, B_1, C_1) = \bar{\varphi}_{A3} + \bar{\varphi}_{B1} + \bar{\varphi}_{C1} - 2\varphi_{mean}$$
$$= 2.233 + 2.093 + 2.217 - 2 \times 2.327 = 1.890$$

Since, the output response for the identified optimal parameters ($A_3B_1C_1$) is not available in Table-2, one of the following deviations due to fictitious parameter could be the correction to the above minimum SCSD value:

$\Delta\bar{\varphi}_{D1} = \bar{\varphi}_{D1} - \varphi_{mean}$ =2.327 – 2.327= 0;

$\Delta\bar{\varphi}_{D2} = \bar{\varphi}_{D2} - \varphi_{mean}$ =2.323 – 2.327= -0.003; and

$\Delta\bar{\varphi}_{D3} = \bar{\varphi}_{D3} - \varphi_{mean}$ =2.330 – 2.327= 0.003

These three corrections are applied individually to the obtained SCSD value of 1.890. One can get three values of φ_e as 1.890, 1.887 and 1.893. The range of φ_e for the optimal input parameters become from 1.887 to 1.893. Analysis value of Ref. [3] for the identified optimal input variables is 1.92, which is found to be close to the determined range. The least and highest deviations are -0.003 and 0.003 respectively. The range (that is the minimum and maximum) of output response can be obtained by superposing the value of φ_e from equation (2) to the minimum and maximum of the three deviations $(\Delta\bar{\varphi}_{Di}, i = 1,2,3)$. Table-4 gives results of SCSD from the additive law for all 27 combinations of parameters and the analysis data [3]. Most of the obtained results from the additive law are in good agreement with test results [3].

Figure-3 shows good comparison of the present analysis results with test data [3]. The test data [3] is found to be close to the range or within the obtained range.

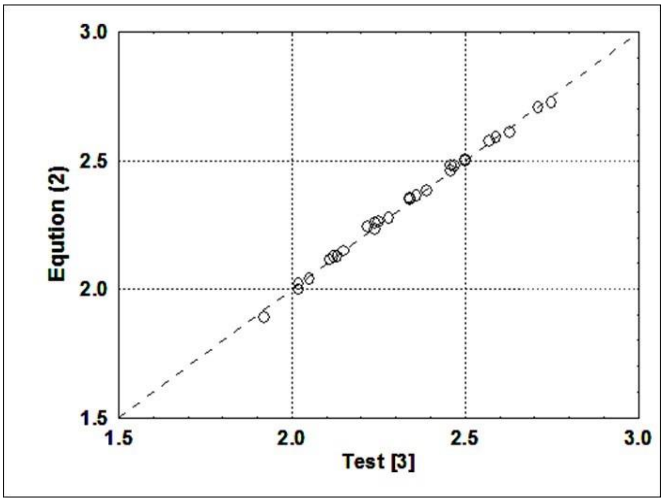

Figure-3: Comparison of SCSD estimates using equation (2) with test data [3].

Table-4: Evaluation of safety coefficient for surface durability (SCSD) from equation (2) for all possible combinations of input variables viz., gear material (A), module (B) and gear width (C).

S. No.	Levels of input variables/ parameters			Safety coefficient for surface durability (SCSD)				
	A	B	C	Ref. [3]	Eq. (2)	Relative Error (%)	Estimated range	
							Minimum	Maximum
1	1	1	1	2.02	2.020	0.0	2.017	2.023
2	1	1	2	2.12	2.127	-0.3	2.123	2.130
3	1	1	3	2.22	2.243	-1.1	2.240	2.247
4	1	2	1	2.24	2.257	-0.7	2.253	2.260
5	1	2	2	2.36	2.363	-0.1	2.360	2.367
6	1	2	3	2.47	2.480	-0.4	2.477	2.483
7	1	3	1	2.46	2.483	-0.9	2.480	2.487
8	1	3	2	2.59	2.590	0.0	2.587	2.593
9	1	3	3	2.71	2.707	0.1	2.703	2.710
10	2	1	1	2.05	2.040	0.5	2.037	2.043
11	2	1	2	2.15	2.147	0.2	2.143	2.150
12	2	1	3	2.25	2.263	-0.6	2.260	2.267
13	2	2	1	2.28	2.277	0.1	2.273	2.280
14	2	2	2	2.39	2.383	0.3	2.380	2.387
15	2	2	3	2.50	2.500	0.0	2.497	2.503
16	2	3	1	2.50	2.503	-0.1	2.500	2.507
17	2	3	2	2.63	2.610	0.8	2.607	2.613
18	2	3	3	2.75	2.727	0.8	2.723	2.730
19	3	1	1	1.92	1.890	1.6	1.887	1.893
20	3	1	2	2.02	1.997	1.2	1.993	2.000
21	3	1	3	2.11	2.113	-0.2	2.110	2.117
22	3	2	1	2.13	2.127	0.2	2.123	2.130
23	3	2	2	2.24	2.233	0.3	2.230	2.237
24	3	2	3	2.34	2.350	-0.4	2.347	2.353
25	3	3	1	2.34	2.353	-0.6	2.350	2.357
26	3	3	2	2.46	2.460	0.0	2.457	2.463
27	3	3	3	2.57	2.577	-0.3	2.573	2.580

V. DEVELOPMENT OF EMPIRICAL RELATION

Using the means values of safety coefficient for surface durability (SCSD) presented in the ANOVA Table-3, it is possible to represent the data of

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$\bar{\varphi}_A$ as a quadratic polynomial of *A*; the data of $\bar{\varphi}_B$ as a quadratic polynomial in *B*; and the data of $\bar{\varphi}_C$ as a quadratic polynomial in *C*.

From equation (2), one can find a quadratic relation for SCSD: $\varphi_e = \bar{\varphi}_A + \bar{\varphi}_B + \bar{\varphi}_C - 2\varphi_{mean}$ in terms of the 3 input variables *A*, *B* and *C*. For the case where an input variable is not a number, it is better to represent such an input variable in a coded form. In the present study, the levels of input variable *A* are gear materials. Hence, $\bar{\varphi}_A$ is represented by a quadratic polynomial function of ξ_1 by defining $\xi_1 = -1$, for the gear material, A_1=16MnCr5; $\xi_1 = 0$, for the gear material, A_2=28Cr4; $\xi_1 = 1$, for the gear material, A_3= C15E. For the case where input variables *B* and *C* are numbers, $\bar{\varphi}_B$ is represented by a quadratic polynomial function of ξ_2 by defining $\xi_2 = \frac{(B-B_2)}{(B_2-B_1)}$; $\bar{\varphi}_C$ is represented by a quadratic polynomial function of ξ_3 by defining $\xi_3 = \frac{(C-C_2)}{(C_2-C_1)}$. Following the above, one can represent the safety coefficient for surface durability (SCSD) in terms of parameters (namely, the gear material (A), module (B), and gear width(C)) in the form

$$SCSD = 2.382 - 0.065\xi_1 - 0.085\xi_1^2 + 0.232\xi_2 - 0.005\xi_2^2 + 0.1115\xi_3 + 0.0055\xi_3^2 \qquad (3)$$

Here $\xi_1 = -1$, for the gear material, A_1=16MnCr5; $\xi_1 = 0$, for the gear material, A_2=28Cr4; $\xi_1 = 1$, for the gear material, A_3= C15E; $\xi_2 = 4B - 10$; and $\xi_3 = \frac{C}{3} - 10$. Table-5 gives comparison of 3 SCSD values obtained from the empirical relation (3) for all possible combinations of 3 input variables with 3 levels yielding 27 test runs.

The range (that is the minimum and maximum) of output response is obtained by superposing the value of *SCSD* from equation (3) to the minimum and maximum of the three deviations ($\Delta\bar{\varphi}_{Di}, i = 1,2,3$). Most of the SCSD values of Ref. [3] are close to or within the estimated range. Figure-4 shows a good comparison between the results obtained from equations (2) and (3). Figure-5 shows that SCSD increases with increasing mode for the specified gear material and gear width. Figures 6 and 7 show the comparison of safety coefficient for surface durability (SCSD) evaluated from the empirical relation (3) with ANN predictions, linear regression model and Test [3]. SCSD evaluated from the empirical relation (3) is closely matching with test data [3].

Table-5: Evaluation of safety coefficient for surface durability (SCSD) from the empirical relation (3) for all possible combinations of input variables viz., gear material (A), module (B) and gear width (C).

S. No.	Input variables			Safety coefficient for surface durability (SCSD)				
	Gear material (A)	Module, B (mm)	Gear width, C (mm)	Ref. [3]	Eq. (3)	Relative Error (%)	Estimated range	
							Minimum	Maximum
1	16MnCr5	2.25	27	2.02	2.020	0.0	2.017	2.023
2	16MnCr5	2.25	30	2.12	2.127	-0.3	2.123	2.130
3	16MnCr5	2.25	33	2.22	2.243	-1.1	2.240	2.247
4	16MnCr5	2.50	27	2.24	2.257	-0.7	2.253	2.260
5	16MnCr5	2.50	30	2.36	2.363	-0.1	2.360	2.367
6	16MnCr5	2.50	33	2.47	2.480	-0.4	2.477	2.483
7	16MnCr5	2.75	27	2.46	2.483	-0.9	2.480	2.487
8	16MnCr5	2.75	30	2.59	2.590	0.0	2.587	2.593
9	16MnCr5	2.75	33	2.71	2.707	0.1	2.703	2.710
10	28Cr4	2.25	27	2.05	2.040	0.5	2.037	2.043
11	28Cr4	2.25	30	2.15	2.147	0.2	2.143	2.150
12	28Cr4	2.25	33	2.25	2.263	-0.6	2.260	2.267
13	28Cr4	2.50	27	2.28	2.277	0.1	2.273	2.280
14	28Cr4	2.50	30	2.39	2.383	0.3	2.380	2.387
15	28Cr4	2.50	33	2.50	2.500	0.0	2.497	2.503
16	28Cr4	2.75	27	2.50	2.503	-0.1	2.500	2.507
17	28Cr4	2.75	30	2.63	2.610	0.8	2.607	2.613
18	28Cr4	2.75	33	2.75	2.727	0.8	2.723	2.730
19	C15E	2.25	27	1.92	1.890	1.6	1.887	1.893
20	C15E	2.25	30	2.02	1.997	1.2	1.993	2.000
21	C15E	2.25	33	2.11	2.113	-0.2	2.110	2.117
22	C15E	2.50	27	2.13	2.127	0.2	2.123	2.130
23	C15E	2.50	30	2.24	2.233	0.3	2.230	2.237
24	C15E	2.50	33	2.34	2.350	-0.4	2.347	2.353
25	C15E	2.75	27	2.34	2.353	-0.6	2.350	2.357
26	C15E	2.75	30	2.46	2.460	0.0	2.457	2.463
27	C15E	2.75	33	2.57	2.577	-0.3	2.573	2.580

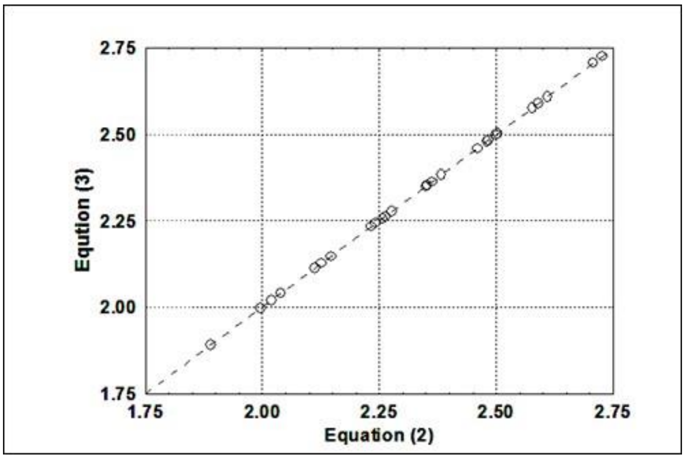

Figure- 4: Comparison of safety coefficient for surface durability (SCSD) evaluated from equations (2) and (3) for the 27 test runs.

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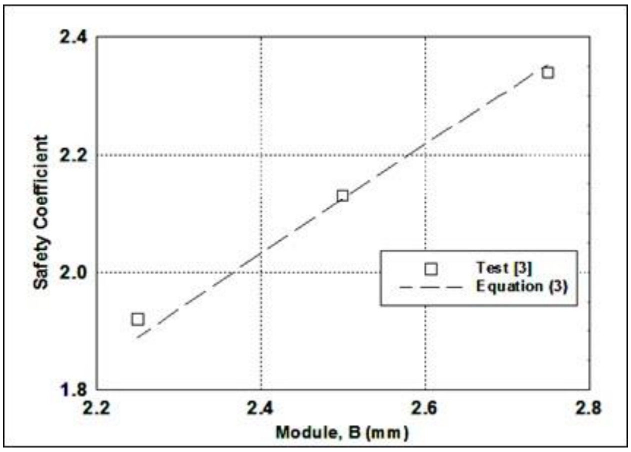

Figure-5: Variation of safety coefficient with module for gear material, A3= C15E and gear width, C1=27mm.

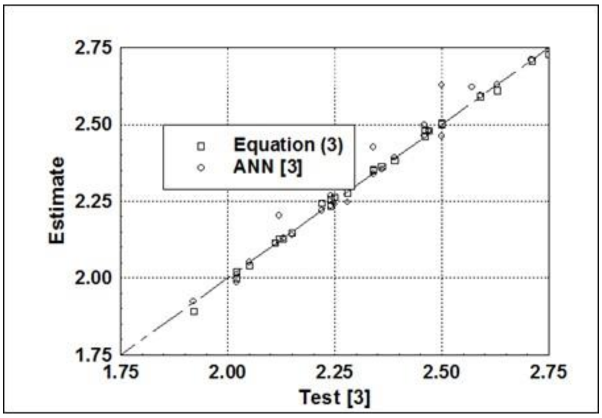

Figure- 6: Comparison of safety coefficient for surface durability (SCSD) evaluated from the empirical relation (3) with ANN predictions and Test [3].

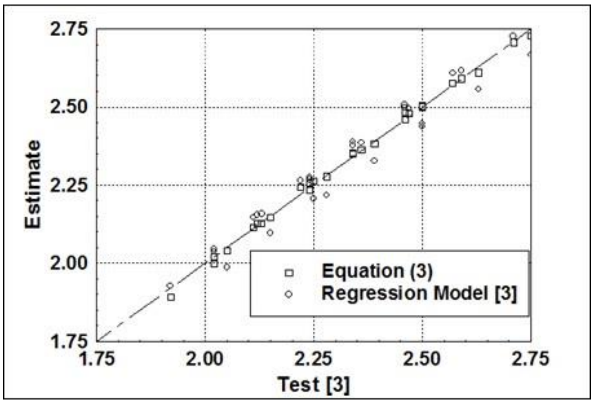

Figure- 7: Comparison of safety coefficient for surface durability (SCSD) evaluated from the empirical relation (3) with the regression model and Test [3].

Industries expect simple and reliable procedures while solving the optimization problems. Taguchi method suggests for applying the S/N ratio transformation when repetition of experiments are planned [15]. Several researchers [23] have examined the adequacy of GRA (grey relational analysis) [17-22], GA (genetic algorithm) [24, 25], TLBA (teacher learning base algorithm) [26], RSM (response surface methodology) [27] and PSO (particle swarm optimization) [28]. None of them have presented the results using the simple Taguchi method. Miladinović and Veličković [3] have made a comment that Taguchi method gives results close to the experimental ones, when compared to those in comparison to the ANN. They have considered the full factorial design of 27 experimental data and applied S/N ratio transformation, whereas the present analysis considers only 9 experiments and presented the expected range of SCSD for the 27 experiments and demonstrated the adequacy of the modified Taguchi approach without applying the S/N ratio transformation.

VI. CONCLUSION

Modified Taguchi approach is considered in this article for selecting optimal input variables or parameters viz., gear material, module and gear width by minimizing the safety coefficient for surface durability (SCSD) of internal planetary gear. The developed empirical relation (3) for SCSD is validated with existing test data for all possible combinations of the input variables. It also provides better results when compared to those obtained from linear regression model and ANN of Miladinović and Veličković [3].

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