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Comparison Study: Taguchi Methodology vis.-a-vis. Response Surface Methodology Through a Case Study of Accelerated Failure in Spin-on-Filter

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Abstract: In this paper we investigate the choice of best combination of factors for 2^7 X 3^1 mixed factorial design in 16 runs through Taguchi Design Method and Response Surface Method (RSM). Further we show that Response Surface Method predicts better optimal response (9.72% more) as compared to optimum response obtained through Taguchi Design Method. The comparison of methods is done with the help Spin-on-Filter case study conducted by [1]. We use MINITAB for the analysis under both methods.

Keywords: Spin-on-filter (SOF); Taguchi Design Method; Signal-to-noise ratio; Response Surface Method; Dynamic life of SOF; Choice of the best factors combination; ANOVA

I. INTRODUCTION

A spin-on-filter (SOF) is an important integral component of oil-operated generator sets and automobiles. It is used for filtering the lubrication oil and fuel. In particular, its function is to remove the unwanted dirt and heavy particles. Thus, this component is useful for preventing the plugging and restriction of injectors. The SOF, while in use goes through various operating load conditions that contribute to wear and tear. As a result, the SOF will, at some point of time, either break off or start leaking at the seamed locations. The number of cycles at which the leak of break starts is defined as the dynamic life of the SOF i.e. variable of our interest, say y. To increase efficiency of the system of which this component is a part it is desirable for higher dynamic life of the SOF. To achieve the desirable result a study was conducted through an newly installed production process. Acceptable dynamic life was set as the survival of filters at least 10^5 cycles. Before undertaking this study, the manufacturing company used conditional process settings in production of the SOFs. It was found that 20% of SOFs did not survive for at least 10^5 cycles. The study of comparison between Taguchi Design Method and Response Surface Method for hybrid microcircuit assembly processing have found in [3]. Further, they show that Response Surface Method has better efficiency than Taguchi Design Method.

II. SOF PRODUCTION PROCESS

The SOF is an assembly of a filter element, shell, nut plate and retainer. Further filter element itself is an assembly of a filter paper, center tube, end plate and spring. The SOF manufacturing process is mainly classified in following eight steps:

(i) Pleating
(ii) Knuckle setting
(iii) Clipping
(iv) End plate attachment
(v) Curing
(vi) Welding
(vii) Seaming
(viii) Screen printing and packing

The details of process steps is given in Dharmadhikari et al (2000).

III. THE DESIGN OF EXPERIMENT FOR THE DYNAMIC LIFE OF SOF

To use statistical approach in designing and analyzing an experiment, it is necessary to follow the basic guideline for conducting the experiment. The basic steps of guideline of design of experiments are:

(i) Recognition and statement of the problem: Here our approach is to investigate choice of best combination of factors as a result optimum value of dynamic life of SOF.

(ii) Choice of factors, levels and ranges: Brainstorming with experienced engineers and feasible operating ranges of machines and materials help to decide the experimental factors.

(iii) Choice of experimental design: The study conducted for eight factors in 16 runs. The seven factors at two levels and eighth factor at three levels. The descriptions of these factors are given in Table 1 following to [1]. In statistical language our objective is to study main effects and interaction effects in this mixed factorial experiment. To conduct such an experiment L_{16} orthogonal array given by Taguchi or simultaneously one can construct through fractional factorial design [2]. We also note that for all factors at level 1 (level 2: B) denotes the level under ongoing practice and level 2 indicates the potential new value of the setting. To analyze the data

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through Taguchi design method we require minimum two replications i.e. the dynamic life of two different SOF of each factor combination are observed. For details regarding Taguchi design method and fractional factorial experiment readers may refer [2].

(iv) Performing the experiment and collection of data: As the experiments are conducted in laboratory or like laboratory environment the experimenter should first create the same environment which is the actual environment for the product outside the laboratory. To carryout test on SOF in laboratory environment is created like environment in automobile engine for SOF. To complete the experiment in limited time frame extra mechanical stress supplied from outside in process i.e. accelerated failure can be observed dynamic life time of SOF. A filter put on test continue to operate without failure until the end of the second day, its life has to be greater than 10^5 cycles. Dynamic life cycles of obtained through a counter. Each filter was put on test and removed upon failure or at the end of the second day, which ever occurred first. This experiment is conducted by [1] and its outcome are given in Table 2. The failure (uncensored) observation and survival SOF observation indicated through status column in Table 2 by 0 and 1 respectively.

(v) Statistical Analysis of Data

(vi) Conclusions and recommendation

Step (v) and (vi) are discussed in details in the section of Statistical Analysis for Taguchi Design Method and Response Surface Method.

IV. STATISTICAL ANALYSIS FOR TAGUCHI DESIGN METHOD AND RESPONSE SURFACE METHOD

A. *Taguchi Design Method*

Here we note that the life of a SOF is a “larger-the better” type of characteristic. The signal-to-noise ratios are calculated through the equation for “larger-the-better” type

$$\eta_i = -\log\left(\frac{1}{n}\sum_{j=1}^{n}\frac{1}{y_{ij}^2}\right) \quad (1)$$

where y_{ij} is the jth observation from the ith run and n is number of replications of the ith run. In our case we have $n = 2$ and values for η_i can be calculated for dynamic life of SOF. The resultant output obtained by analyzing data in Table 2 using MINITAB software is given in Table 3. Here again it is to be noted that Taguchi design is analysed for main effects for all factor and one interaction AB suggested by engineers.

In Taguchi Design Method the level of factor is considered for optimum response is based on the maximum value of signal-to-noise ratio among the levels of each factor. The resultant recommended level of factors for the production of dynamic life of SOF having optimum life is given in Table 4.The predicted dynamic life for the recommended choice of factor combinations can be obtained through inverting the optimum noise-to-signal ratio as a function of y. The optimum value of noise-to-signal ratio for the factor combination recommended in Table 4 is 102.00 and corresponding optimum dynamic life of SOF is 1,12,434 cycles more than 10^5 cycles.

B. *Response Surface Method*

Response Surface Methodology (RSM), is a collection of mathematical and statistical techniques that are useful for modelling and analysing of problems in which a response of interest is influenced by several variables (factors) and objective is to optimize this response[2].

In RSM problems, the form of the relation is unknown. Thus the first step is to find approximate functional relationship between y and set of independent variables $\underline{x}$. The statistical form of RSM:

$$y = f(\underline{x}) + \varepsilon \quad (2)$$

where ε represents the noise or error observed in the response y. Our objective is to investigate the best choice factor combination which gives optimum value of response on the surface of responses. The first step of RSM is to investigate the distribution of average dynamic life of SOF (avelife). The distribution of average dynamic life of SOF is found to be Normal from its Normal Probability Plot (Figure 2). One can refer for detail [3-4]. Further the p-value of Anderson-Darling test of fitting of normal distribution for avelife is 0.644 (> 0.05) which indicates, the normal distribution fits well to avelife of SOF.

Before fitting RSM to the data given in Table 2 to identify which effect terms to be included in the model we draw main effect plots and interaction effect plots for all factors given in Figure 3((a)-(b)).

The analysis of average dynamic life of SOF is carried out through option of Response Surface in MINITAB by providing all main effects and possible interactions effects from interaction plots. This analysis is done for un-coded observations in MINITAB. The resultant output is given in Table 5 (Estimates of effects) and Table 6 (Analysis of Variance Table)

The value of goodness of fit R-Square for fitted model is 85.6% which indicates that 85.6% of total variation of dynamic life of SOF is explained by the fitted model. Further from Table 6 of Analysis of Variance of SOF, the p-value for linear and interaction term are greater than 0.05 suggest that first order Response Surface model is sufficient to obtain optimum value of dynamic life of SOF.

In Table 5 of estimated regression coefficients, it is observed that all main effects are insignificant at 5% level of significance and interaction effect AG is only significant at 5% level of significance because p-value correspond to interaction effect AG is 0.045 (< 0.05). Therefore, the fitted Response Surface model for average dynamic life of SOF is

$$\begin{aligned} y = {} & 187420 - 4526x_1 + 8120x_2 - 37483x_3 \\ & + 10825x_4 - 1474x_5 - 2887x_6 - 56492x_7 \\ & - 45131x_8 - 520x_1x_2 + 40598x_1x_7 + 21695x_1x_8 \end{aligned} \quad (3)$$

From study of main effect plots of average dynamic life SOF for all factors (Figure 3(a)), the recommended best combination of level of factors is given in Table 7.

The optimum value of y for above recommended levels of factor for the production of SOF using equation (3) is 1,

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23,926 cycles. Further, it is to be noted that RSM would give 9.72% more optimal value compared to Taguchi method.

V. CONCLUSION AND RECOMMENDATION

In Section 4 we obtain the optimum value of average dynamic life of SOF through Taguchi method and Response Surface Methodology is 112,434 and 123,926 respectively. From these two numbers of life cycle we can say RSM gives 9.72% more optimal value compared to Taguchi method.

A. *ADVANTAGES OF USING RESPONSE SURFACE METHODOLOGY*

1. It is a Statistical/Mathematical modelling technique.
2. It can help to find optimum value for response beyond or within the range of level of factors suggested by engineers.
3. It will help to identify the future direction of optimum response, at where optimum can possible.
4. It can also identify the interaction or curvature effects beyond the imagination of engineers.
5. It can also investigate statistical significance of effects. As a result on can construct 95% confidence interval for the values such effects which can help to identify future range of level of factors.

B. *DISADVANTAGES OF TAGUCHI DESIGN METHOD*

1. It is purely a philosophical, no Mathematics involved.
2. It gives only the optimum value at any levels specified by experimenter
3. It will not give the future direction of optimum response in experiments. Further, the future direction of optimum require to conduct one more new experiment

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[5] http://en.wikipedia.org/wiki/Oil_filter

Figure 1: Image of Spin-on-Filter (SOF) used in Automobile [5]

Figure 2: Normal Probability Plot of Average Life Cycle of SOF

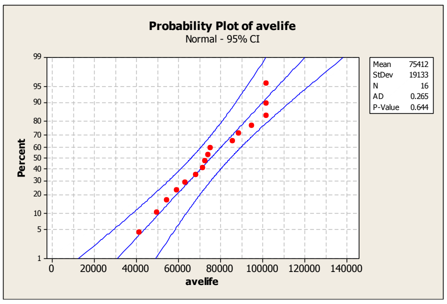
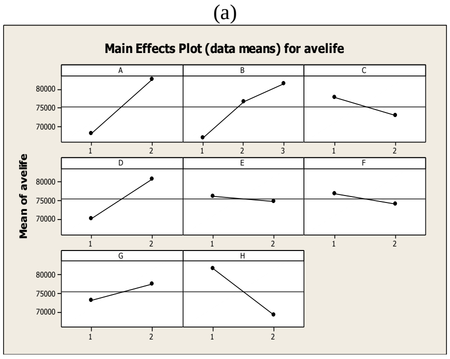


Figure 3: Main Effect Plots and Interaction Effect Plots for avelife

(a)



(b)

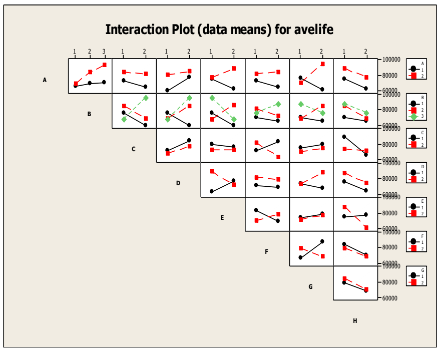


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Table 1: Factors and their Levels

Description	Process	Factor (variable)	Present level	Experimental levels			Unit
				1	2	3	
Air Pressure	Welding	A (x_1)	25	25	32	-	psi
Stroke Pressure	Welding	B(x_2)	101	100	101	102	mm
Nut plate retainer concentricity	Welding	F(x_6)	<0.03	<0.03	0.03-0.06	-	in.
Roller-1 horizontal gap	Seaming	C(x_3)	0.114	0.114	0.112	-	in.
Roller-2 horizontal gap	Seaming	D (x_4)	0.095	0.095	0.093	-	in.
Roller-1 vertical gap	Seaming	H (x_8)	0.05	0.05	0.15	-	in.
Roller-2 vertical gap	Seaming	E (x_5)	0.05	0.05	0.15	-	in.
Lip width		G (x_7)	3.45	3.45	3.95	-	mm

Table 2: Experimental Design and Outcome of Experiments

Run No.	A	B	C	D	E	F	G	H	Status#	life	Status#	Life
1	1	1	1	1	1	1	1	1	0	101,962	1	48,635
2	1	1	2	2	2	2	2	2	1	50,110	1	58,947
3	2	1	1	1	1	2	2	2	1	72,737	1	76,003
4	2	1	2	2	2	1	1	1	0	101,962	1	24,770
5	1	2	1	2	2	1	1	2	1	71,235	1	65,320
6	1	2	2	1	1	2	2	1	1	65,664	1	17,550
7	2	2	1	2	2	2	2	1	0	101,962	0	101,962
8	2	2	2	1	1	1	1	2	1	48,136	1	70,770
9	1	3	1	1	2	1	2	2	1	50,539	1	48,850
10	1	3	2	2	1	2	1	1	1	75,710	0	101,962
11	2	3	1	1	2	2	1	1	1	69,615	0	101,962
12	2	3	2	2	1	1	2	2	0	101,962	0	101,962
13	1	2	1	2	1	1	2	1	1	87,701	0	101,962
14	1	2	2	1	2	2	1	2	1	41,692	0	101,962
15	2	2	1	2	1	2	1	2	1	43,708	0	101,962
16	2	2	2	1	2	1	2	1	0	101,962	0	101,962

#1: uncensored observation; 0: censored observation

Table 3: Response Value Table for Signal-to-Noise Ratio

Level	**Factor**							
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**
1	95.20	94.64	97.10	95.36	96.16	96.49	95.61	96.35
2	97.11	96.11	95.21	96.74	96.14	95.82	96.69	95.96
3	-	97.74	-	-	-	-	-	-

Table 4: Recommended Levels of Factors for the Production of SOF

	Factor							
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Level	2	3	1	2	1	1	2	1

Table 5: Estimated Regression Coefficients for Average Dynamic Life of SOF

Term	**Coefficient**	**SE coefficient**	**T**	**P-value**
Constant	187420	54806	3.420	0.027*
A	-45256	35854	-1.262	0.275
B	8120	21673	0.375	0.727

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C	-37483	30650	-1.223	0.288
D	10825	7032	1.539	0.199
E	-1474	7032	-0.210	0.844
F	-2887	7032	-0.411	0.762
G	-56492	22236	-2.541	0.064
H	-45131	30650	-1.472	0.215
AB	-520	14063	-0.037	0.972
AG	40598	14063	2.887	0.045*
CH	21695	19888	1.091	0.337

S=14063 R-sq = 85.6% * p-value(<0.05)

Table 6: Analysis of Variance of Average Dynamic Life of SOF

Source	DF	Adj. SS	Adj. MS	F	P-value
Regression	11	470020009	427290917	2.16	0.238
Linear	8	2453608926	306701116	1.55	0.354
Interaction	3	209682907	698943069	3.53	0.127
Residual Error	4	791084178	197771044		
Total	15				