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Ceiling Fan Vibration Analysis: Response Surface Method

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Abstract
Vibration is the motion of a particle or a body or system of connected bodies displaced from a position of equilibrium. Most vibrations are undesirable in machines and structures because they produce increased stresses, energy losses, wear, increase bearing loads, induce fatigue, create passenger discomfort, and absorb energy from the system. Rotating machine parts need careful balancing in order to prevent damage from vibrations. Vibration occurs when a system is displaced from a position of stable equilibrium. The system tends to return to this equilibrium position under the action of restoring forces such as the elastic forces, as for a mass attached to a spring, or gravitational forces, as for a simple pendulum. The system keeps moving back and forth across its position of equilibrium. A system is a combination of elements intended to act together to accomplish an objective. In ceiling fan different causes of Vibration might be Number of blades, blade cord width, blade thickness, blade length, blade angle, blade tip angle, blade tip level, blade materials, coupling structural resonance, drive shaft, unbalancing, pitch angle, fan speed, structural member in the flow path, ventilators, distance from ceiling, environmental parameter, room size, power required, capacitor, rotor, casting, winding, bearing, electric motor, etc. So it is important to correlate input parameters with output parameters to decide their impacts on Vibration in ceiling fan.

Keywords: *Ceiling Fan, Response Surface Method, Sensitivity Analysis, Optimization, MINTAB 16.*

1. Introduction

Machines in the most excellent of operating condition will have some vibration because of small, minor defects [11]. Therefore, each machine will have a level of vibration that may be regarded as normal or inherent. However, when machinery vibration increases or becomes excessive, some mechanical trouble is usually the reason. The response surface methodology (RSM) is helpful in developing a suitable approximation for the true function relationship between the independent variables and the response variable that may characterize the power level for ceiling fan [12]. It has been proved by several researchers that efficient use of statistical design of experimental techniques; allow development of an empirical methodology, to incorporate a scientific approach in analysis of ceiling fan vibration. Even though sufficient literature is available on analysis of ceiling fan vibration, no systematic study has been reported so far to correlate the process parameters and vibration. Hence, in this investigation, the design was used to conduct experiments for exploring the interdependence of the process parameters and second order mathematical model for vibration was developed from the data obtained by conducting the experiments.

2. Experimental Important Variables.

Many autonomously controllable parameters affecting vibrations may be Fan Blades (A), Room volume (B), Downrod length (C), Fan speed (D) were selected as primary variables for the study. These variables are contributing to the vibration in the ceiling fan. Distinctive combinations of variables were used to carry out the experimental runs [10]. This was carried out by varying one of the factors while keeping the rest of them at constant values.

2.1 Conducting Experiments

Experiments are conducted by choosing three different Ceiling fans of various blades mainly (2, 3, 4), three different room size, three different rod length, and three different positions of regulator knob. We have taken two ceiling fans, three rooms, three downrods and three knob positions for 27 runs / readings. Using FFT analyzer, vibrations in m/s^2 were recorded. Number of blades, Volumes of rooms, Length of downrods was measured as in observation Table 1. Vibration reading of ceiling fan having different blades, in different room, using different rod at different regulator knob position were recorded as in observation Table 2. By using MINITAB 16 we created a model and optimized it [7]. Different plots like residual plot, surface plot, contour plot, optimization plot were obtained for the result and conclusion.

Table 1: Parameters Level selected for the Experimentation

Parameters	**Levels**		
	Low (1)	**Medium (2)**	**High (3)**
Fan(A)	2	3	4
Room Size (m3)(B)	66.56	167.19	355.84
Rod Length (Inch)(C)	6.5	10.25	12
Speed Knob Position(D)	2	3	4

3. Development of Mathematical Model

3.1 Response Surface Methodology

Response surface methodology (RSM) is a collection of mathematical and statistical technique useful for analyzing problems in which several independent variables or responses are considered to optimize the desired output [7]. In many experimental conditions, it is possible to represent independent factors in quantitative form as given in Eq.(1).Then these factors can be thought of as having a functional relationship or response as follows:

$Y=\Phi(x_1,x_2,\ldots,x_k)$………………………………….. Eq.(1).

Between the response Y and x1, x2, …, xk of k quantitative factors , the function Φ is called response surface or response function. The residual error measures the experimental errors. For a given set of independent variables, a characteristic surface is responded [10].When the mathematical form of Φ is not known, it can be approximate satisfactorily within the experimental region by polynomial. In the present investigation, RSM has been applied for developing the mathematical model in the form of multiple regression equations for quality characteristics of vibration. In applying the response surface methodology, the independent variable was viewed as surface to which a mathematical model is fitted The second order polynomial (regression) equation used to represent the response surface Y is given by

$Y= b_o+\sum b_i x_i+\sum b_{ii} x_i+\sum b_{ij} x_i{*}j+e$…………………… Eq.(2).

Table 2: Observation Table

Experimental Run	**Input**			**Output**	
	Room volume (m3)	**Downrod length (m)**	**Regulator Knob Position**	**Vibration of Fan 1 (m/s^2)**	**Vibration of Fan 2 (m/s^2)**
				Y_1	**Y_2**
1	66.56	0.1651	2	2.19	1.99
2	66.56	0.1651	2	2.23	2.02
3	66.56	0.1651	2	2.22	2.12
4	66.56	0.26035	3	3.31	2.52
5	66.56	0.26035	3	3.28	2.63
6	66.56	0.26035	3	3.63	2.54
7	66.56	0.3048	4	3.95	3.52
8	66.56	0.3048	4	3.52	3.59
9	66.56	0.3048	4	2.98	3.78
10	167.19	0.1651	3	1.9	2.64
11	167.19	0.1651	3	2.58	3.63
12	167.19	0.1651	3	3.66	3.59
13	167.19	0.26035	4	3.64	3.79
14	167.19	0.26035	4	3.09	4.31
15	167.19	0.26035	4	3.55	4.68
16	167.19	0.3048	2	2.26	2.17
17	167.19	0.3048	2	2.63	2.68
18	167.19	0.3048	2	2.32	2.24
19	355.84	0.1651	4	4.53	3.74
20	355.84	0.1651	4	4.82	6.65
21	355.84	0.1651	4	2.32	4.65
22	355.84	0.26035	2	1.96	1.37
23	355.84	0.26035	2	2.05	2.78
24	355.84	0.26035	2	2.77	2.92
25	355.84	0.3048	3	2.63	2.07
26	355.84	0.3048	3	2.17	2.57
27	355.84	0.3048	3	2.66	2.62

3.2 Response Surface Regression

Y1 and Y2 versus A, B, C The analysis was done using coded units. In order to estimate the regression coefficients, a number of experimental design techniques are available [10]. In this work, table 3 and 4 are used which fits the second order response surfaces very accurately. Central composite face cantered design matrix .The final modal was developed using only these coefficient and the final mathematical model to estimate vibration is given by

Second order Response Surface Model for the fan 1 Vibration response is as given below :

Vibration (Y_1) =
0.08778 - 0.29333 * A + 2.67556 * B + 0.30278 * C + 0.10889 * A2-0.37333 * B2-0.18500 * C2 - 0.52444 * A * B -0.41444 * A * C… ……………………..…….Eq.(3).

Second order Response Surface Model for the fan 2 Vibration response is as given below:

Vibration (Y_2) =
0.54778 + 1.182111 * A + 0.78056 * B – 0.89222 * C - 0.29889 * A2 – 0.04500 * B2 – 0.31833 * C2 – 0.40556 * A * B -0.22222 * A * C ……………………..…… Eq.(4).

Table 3: Estimated Regression Coefficients for Y_1 in uncoded units

Term	Coef	SE Coef	T	P
Constant	0.08	1.934	0.045	0.964
A	-0.29	1.156	-0.254	0.803
B	2.67	1.503	1.77	0.092
C	0.3	1.129	0.268	0.792
A*A	0.1	0.248	0.438	0.666
B*B	-0.37	0.286	-1.302	0.209
C*C	-0.18	0.286	-0.645	0.527
A*B	-0.52	0.286	-1.829	0.084
A*C	0.41	0.286	1.44	0.166

Table 4: Estimated Regression Coefficients for Y_2 in uncoded units

Term	Coef	SE Coef	T	P
Constant	0.547	2.02	0.27	0.79
A	1.821	1.211	1.5	0.15
B	0.78	1.576	0.495	0.626
C	-0.897	1.183	-0.758	0.458
A*A	-0.298	0.26	-0.148	0.266
B*B	-0.045	0.3	1.059	0.304
C*C	0.318	0.3	1.05	0.304
A*B	-0.405	0.3	-.1.34	0.194
A*C	0.222	0.3	0.739	0.469

3.3 Checking Adequacy of Model

The adequacy of the developed model was tested using the analysis of variance(ANOVA) technique and the results of second order response surface model fitting in the form of analysis of variance (ANOVA) are given in Table 5and 6. The determination coefficient (R2) indicates the goodness of fit for the model. In this case, the value of the determination coefficient (R1=0.969 98) indicates that only less than 3% of the total variations are not explained by the model. The value of adjusted determination coefficient (adjusted R1=0.5892 and R2=0.7725) are also high, which indicates a high significance of the model. The value of probability＞F in Table 5and 6 for model is less than 0.05, which indicates that the model is significant. In the same way, room size(A), Down Fan rod length (B) and Regulator knob position (C), interaction effect of Room size with down fan rod length (AB), interaction effect of down fan rod length with and Regulator knob position (BC), and second order term of Room size (A) Down Fan rod length(B) and Regulator knob position (C), have significant effect [7]. Lack of fit is non significant as it is desired. The normal probability plot of the residuals for Vibration is shown.

3.4 Experimental Setup

Model-1 : (Fan 1 Vibration)
Response Surface Regression: Y1 versus A, B, C
The analysis was done using coded units.
Estimated Regression Coefficients for Y1

Table 5: ANOVA results for the Vibration of Fan 1.

Source	DOF	Square SS	Adjusted SS	Mean Square	F Value	*p*-value probability > *F*
Regression	8	9.5526	9.5526	1.19408	3.23	0.019
Linear	3	7.9234	1.28525	0.42842	1.16	0.353
A	1	0.1089	0.02383	0.02383	0.06	0.803
B	1	0.0983	1.17141	1.17141	3.17	0.092
C	1	7.6963	0.02662	0.02662	0.07	0.792
Square	3	0.2725	0.78582	0.26194	0.71	0.560
A * A	1	0.0711	0.07114	0.07114	0.19	0.666
B * B	1	0.1656	0.62720	0.62720	1.69	0.209
C * C	1	0.0358	0.15401	0.15401	0.42	0.527
Interaction	2	1.3767	1.37672	0.68836	1.86	0.184
A * B	1	0.6038	1.23769	1.23769	3.34	0.084
A * C	1	0.7729	0.77294	0.77294	2.09	0.166
Residual Error	18	6.6615	6.66147	0.37008		
Pure Error	18	6.6615	6.66147	0.37008		
Total	26	16.2141				
Std deviation	0.60834			R^2	0.5892	
Press	14.9883			Adjusted R^2	0.4066	
				Predicted R^2	0.0759	

Model-2 (Fan 2 Vibration)
Response Surface Regression: Y2 versus A, B, C

Table 6: ANOVA results for the Vibration of Fan 2.

Source	DOF	Square SS	Adjusted SS	Mean Square	F Value	*p*-value probability > *F*
Regression	8	24.8527	24.8527	3.10658	7.64	0.000
Linear	3	21.9187	1.4979	0.49929	1.23	0.329
A	1	1.2064	0.9184	0.91840	2.26	0.150
B	1	1.8625	0.0997	0.09970	0.25	0.626
C	1	18.8498	0.2337	0.23371	0.57	0.458
Square	3	2.1916	1.0249	0.34163	0.84	0.490
A * A	1	0.5360	0.5360	0.53601	1.32	0.266
B * B	1	0.0262	0.0091	0.00911	0.02	0.883
C * C	1	1.6293	0.4560	0.45601	1.12	0.304
Interaction	2	0.7424	0.7424	0.37120	0.91	0.419
A * B	1	0.5202	0.7401	0.74014	1.82	0.194
A * C	1	0.2222	0.2222	0.22222	0.55	0.469
Residual Error	18	7.3202	7.3202	0.40668		
Pure Error	18	7.3202	7.3202	0.40668		
Total	26	32.1729				
Std deviation	0.63771			R^2	0.7725	
Press	16.4704			Adjusted R^2	0.6713	
				Predicted R^2	0.4881	

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Residual Plots

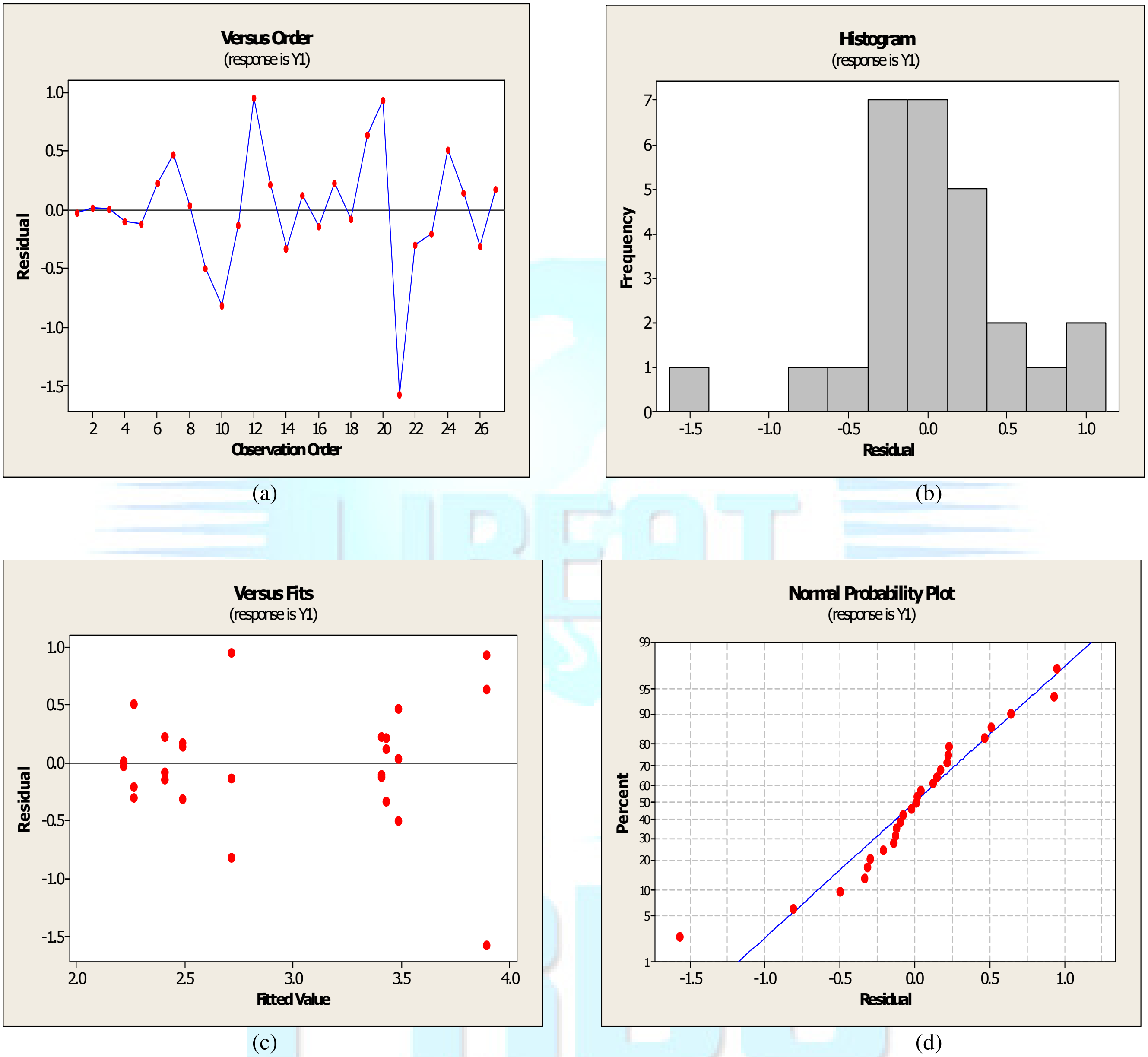
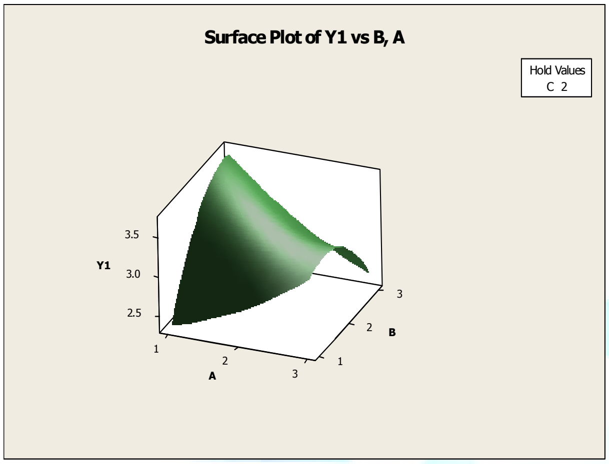
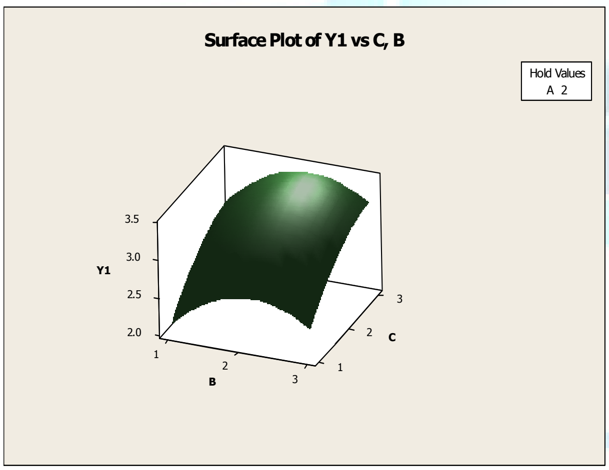


Fig 1 Residual plot for the Vibration of ceiling fan 1.

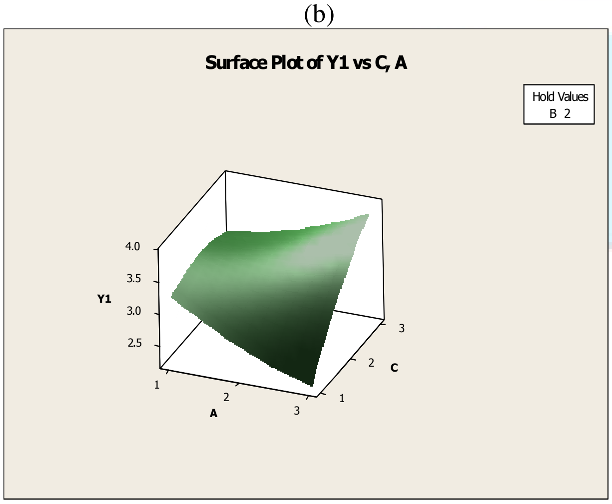
Surface Plot



(a)



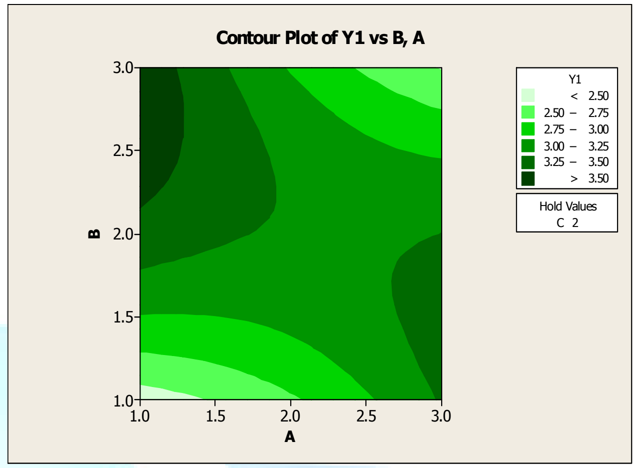
(b)



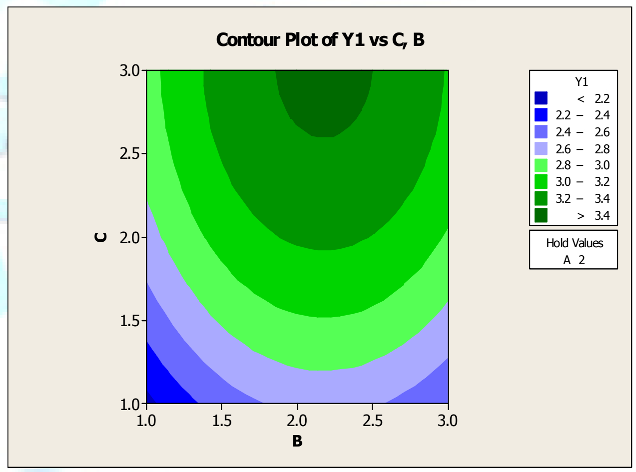
(c)

Fig 2 3D Surface plot for the Vibration of ceiling fan 1.

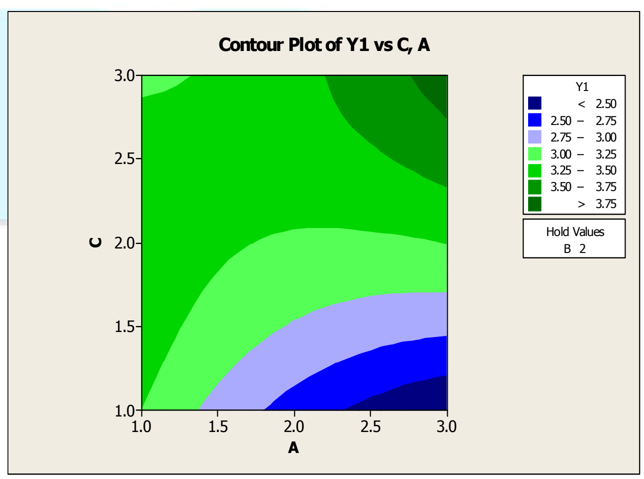
Contour Plot



(a)



(b)



(c)

Fig 3 Contour plot for the Vibration of ceiling fan 1.

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Optimization of Model 1

Response Optimization Parameters

Goal	Lower	Target	Upper	Weight	Import
Y_1 Minimum	1.9	1.9	2.92	1	1

Global Solution

A = 3
B = 3
C = 1

Predicted Responses

Y1 = 1.49556
Desirability = 1.00000
Composite Desirability = 1.00000

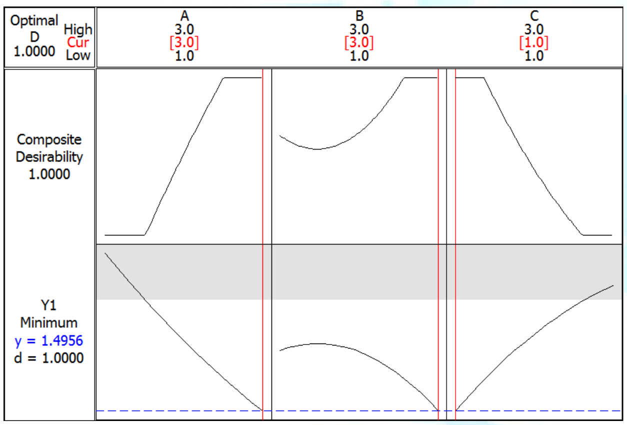
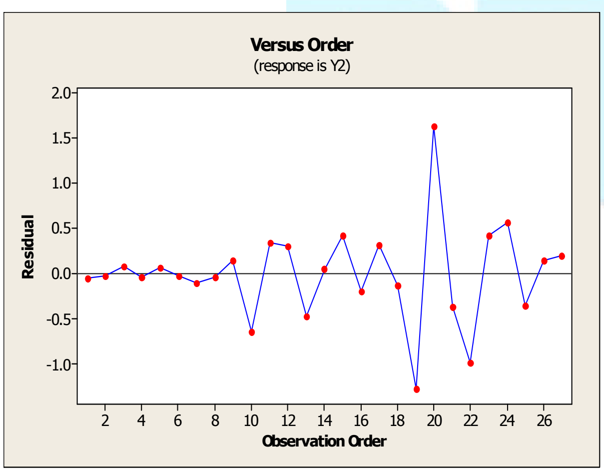
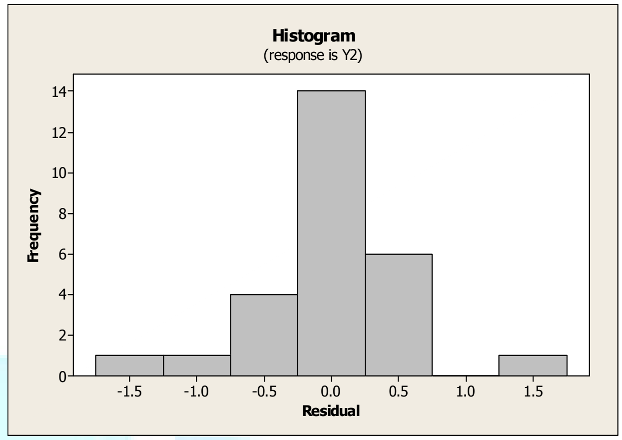


Fig 4 Optimization plot for the Vibration of ceiling fan 1.

Residual Plots



(a)



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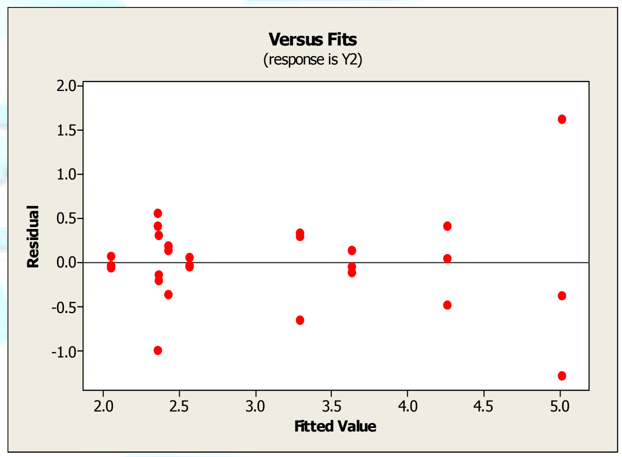

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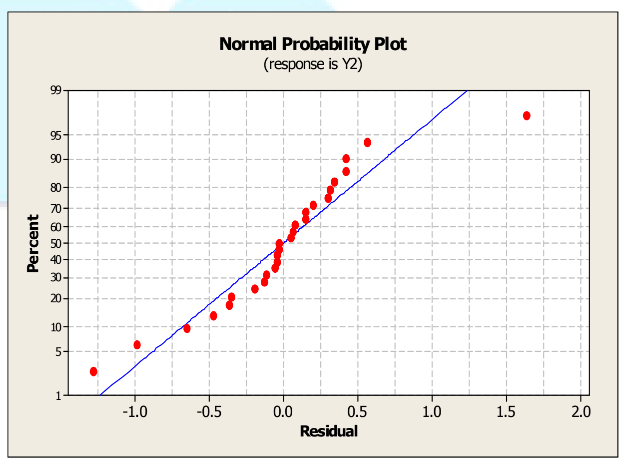
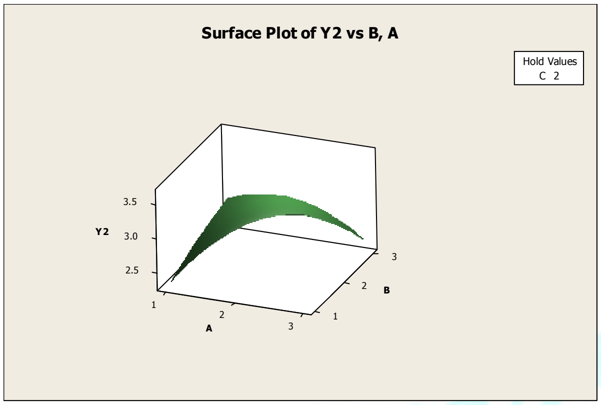


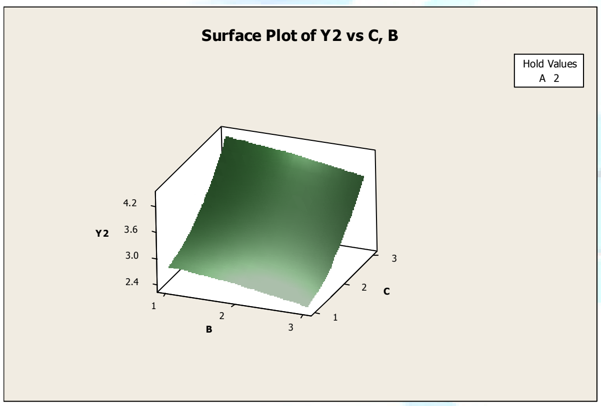
(d)

Fig 5 Residual plot for the Vibration of ceiling fan 2.

Surface Plot



(a)



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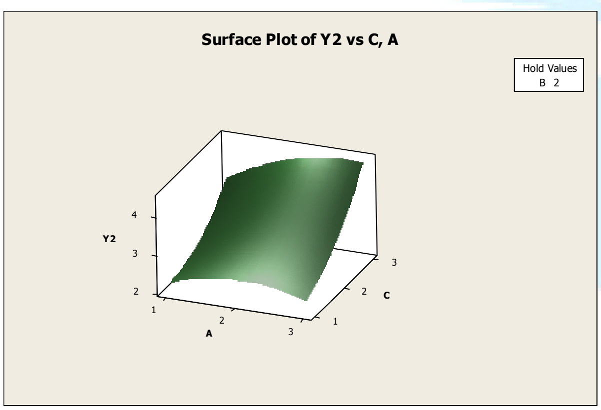
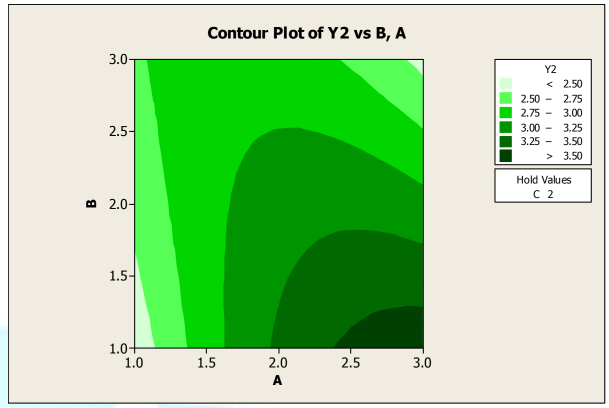


(c)

Fig 6 3D Surface plot for the Vibration of ceiling fan 2

Contour Plot



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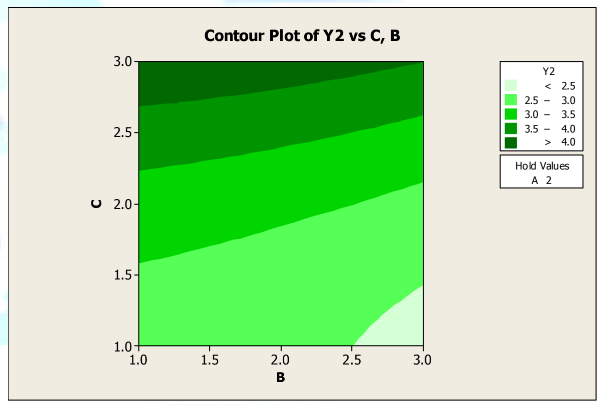

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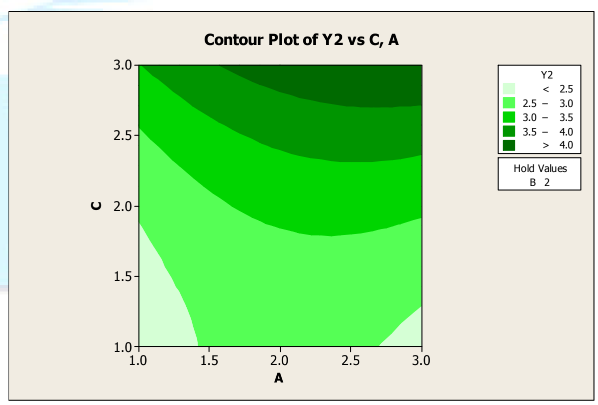

(c)

Fig 7 Contour plot for the Vibration of ceiling fan 2

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Optimization of Model 2
Response Optimization Parameters

Goal	Lower	Target	Upper	Weight	Import
Y_2 Minimum	1.37	1.37	3.1	1	1

Global Solution

A = 3
B = 3
C = 1

Predicted Responses

Y1 = 1.69556
Desirability = 0.81181
Composite Desirability = 0.81181

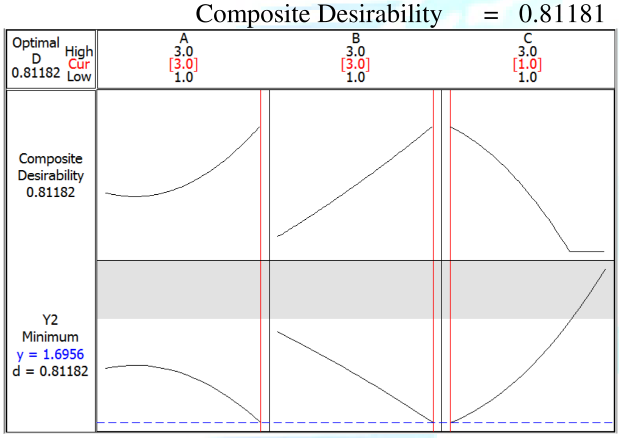

Fig 8 Optimization plot for the Vibration of ceiling fan 2.

3.4 Sensitivity analysis

Sensitivity analysis, a method to identify critical parameters and rank them by their order of importance, is paramount in model validation where attempts are made to compare the calculated output to the measured data [10]. This type of analysis can study which parameter must be most accurately measured, thus determining the input parameters exerting the most influence upon model outputs. Mathematically, sensitivity of a design objective function with respect to a design variable is the partial derivative of that function with respect to its variables. To obtain the sensitivity equation for room size, down rod Length and regulator knob position Eq.(3) and Eq. (4) are differentiated with respect to room size. Sensitivity values for room size , down rod Length and regulator knob position are given in the Table 7.

4. Results and Conclusion

We can achieve the targeted value, 1.49 m/s^2 of vibrations from optimization plot for Fan1 by using 2 blades, room volume 355.84 m3, rod length 12 inch and knob at 1st position. Similarly from the optimization plot we can achieve the targeted value 1.695 m/s^2 of vibrations for Fan-2 by using 3 blades, room volume 355.84 m3, rod length 12 inch and knob at 1st position.

Table 7: Sensitivity Analysis.

				Model 1			Model 2		
S.N.	Room Size (A)	Downrod Length (B)	Regulator Knob Position (C)	$\partial y1/\partial A$	$\partial y1/\partial B$	$\partial y1/\partial C$	$\partial y2/\partial A$	$\partial y2/\partial B$	$\partial y2/\partial C$
1	66.56	6.5	2	9.91	-37.05	-27.9	-40.95	-26.76	-16.8
2	66.56	10.25	3	7.53	-39.84	-28.36	-42.73	-27.13	-17.44
3	66.56	12	4	6.2	-41.15	-28.73	-43.66	-27.25	-18.21
4	167.19	6.5	2	31.75	-89.78	-69.65	-101.28	-67.51	-39.89
5	167.19	10.25	3	29.37	-92.57	-70.02	-103.02	-67.87	-40.19
6	167.19	12	4	28.04	-93.88	-70.39	-103.29	-68.01	-38.93
7	355.84	6.5	2	72.69	-188.63	-147.7	-214.13	-144.09	-40.55
8	355.84	10.25	3	70.31	-191.43	-148.12	-215.2	-144.43	-80.437
9	355.84	12	4	68.98	-192.73	-148.49	-216.14	-144.59	-81.067

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