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Research Article

Parametric Optimization of Pancake Type Load Cell Using Response Surface Methodology

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Abstract

Providing product with good functioning and in least price is very necessary in today's competitive market. Optimization approach is the best approach for industrial component which are having large number of design variables with more than one objective to satisfy for mobility of tomorrow. Load cells are transducers employed to measure force or weight. In the present investigation an attempt has been made on parametric optimization of pancake type strain gauge based load cell. The study focuses on finding critical dimensional parameters of the pancake type load cell and its effect on sensitivity and volume. The finite element method (FEM) has been applied at various levels of typical dimensional parameters of load cell. The response surface methodology (RSM) is employed for multi objective optimization of responses for maximizing sensitivity and minimum volume. Response optimizer with desirability function is found for optimum results of response surface methodology. Analysis of variance (ANOVA) is conducted for analyzing contribution of each parameter on the performance of load cell.

Keywords: *ANOVA, FEM, Load cell, RSM, Strain gauge, Sensitivity, Volume*

1. Introduction

Among the complete range of sensors and transducers used in automotive, research, consumer and industrial applications, load cells stand out as one of the most significant transducers. Basically, these transducers used to calculate deformations produced by force [Hernandez *et.al*, 2006]. According to the type of output signal they produce and the way they detect the weight, there are many types of load cells, strain gauges, mechanical cells, and other types (fiber optic, piezoresistive, and so on). However, due to high precision and low cost, strain gauge load cells are the most used in industries. Majority of load cell designs, use strain gauges as the sensing element. The deformation applied on metallic elements shows variations in electrical resistance significantly. The same metallic string can differ in electrical resistance depending on whether it is extended or contracted. The longer the metallic string becomes, the larger the resistance. The strain gauge utilizes this principle and detects a strain by changes in resistance. A load cell is made by bonding strain gauges to a spring material. To efficiently detect the strain, strain gauges are bonded to the location on the spring material where the strain will be the largest .When the stress caused by external force to an object is below the proportional limit, the strain varies linearly with the stress. In addition, when external force is applied to a force transducer and its spring material is deformed (strained), the resistance value of the strain gauge varies linearly with the deformation (Thein *et.al*, 2013), (Roman *et.al*, 2010), (Thakkar, 2013).

Finite Element Analysis is an engineering analysis technique that is utilized to simulate the behavior of complex structures for which no exact solutions exist. While it has its historical beginnings in structural analysis, finite element analysis is now applied to a wide variety of engineering areas, including fluid flow, heat transfer, and electromagnetic. Finite element analysis software package (Hyperworks) used in current research for structural analysis of load cell.

For current research Pancake' type load cell chosen which is also known as button type design uses strain gauges to examine the stress in the sensing element when subjected to a compression force. Shape optimization is a process of changing the physical dimensions of a structural part to increase sensitivity and reduce the volume. Multi-objective optimization of sensitivity and volume parameters were investigated by response surface methodology.

2. Methodology of Work

2.1. Description of load cell

Serial no- 12/98-175 'pancake' type load cell which is manufactured by Fuel Instrument And Engineering Pvt. Ltd. Parvati Co. Op. Industrial estate Yadrav-

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416145 having capacity of 500kgf. Whose dimensions are shown in figure 1 is chosen for finding critical dimensional parameters and its effect on sensitivity and volume. The material used for this load cell is EN 24Steel having high wear resistance, high toughness and strength property with its, Young's Modulus $2.1 \times 10^5 N/mm^2$, Poisson Ratio 0.3, Yield strength $600 N/mm^2$ and material density $7840 \times 10^{-5} Kg/mm^3$ (Kamble et. al, 2012), (Ghanvat *et.al*, 2012).

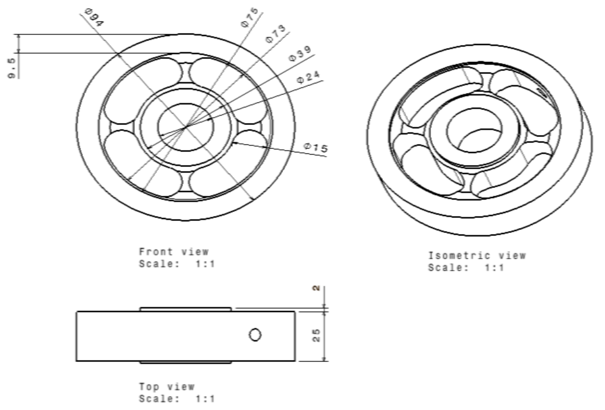
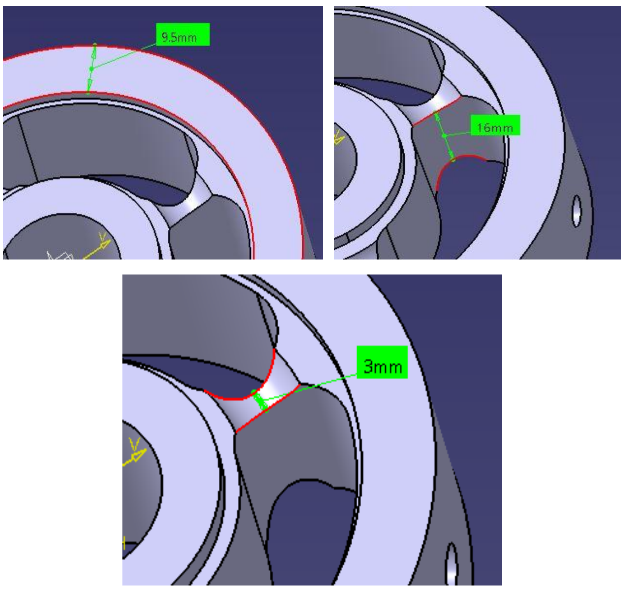


Fig.1 'Pancake' type load cell

2.2. Selection of Parameters and Levels

The various dimensional parameters studied that are outer diameter, inner diameter, height, width, web height, web thickness. According to design theory the maximum failure area is that in which maximum stress is induced (Bethe, 1994). So based on this theory the Rim thickness, web height and web thickness this critical dimensional parameters are considered.



Rim thickness [A] Web height [B] Web thickness [C]

Fig.2 Critical dimensional parameters

Table 1 Level of Critical Parameters

S.No	Factors	Notations	Units	Level 1	Level 2	Level 3
1	Rim thickness	A	mm	7.6	9.5	11.4
2	Web height	B	mm	12.8	16	19.2
3	Web thickness	C	mm	2.4	3	3.6

2.3. Experimental Design

Required experiments for the RSM were designed using the box-behnken method and performed by FEM. This design was based on a 3×3 factorial design, three replicates of the central run, leading to 10 sets of experiments, enabling each experimental response to be optimized. The responses were investigated using a box–behnken statistical experimental design. All experiments were performed in standard order to minimize the effects of uncontrolled factors that may introduce a bias in the response.

This helps in achieving high quality with fewer losses. In this work, it helps to achieve following objectives.

- Optimizing dimensional parameters for Sensitivity and Volume.
- To estimate the contribution of each parameter for response values.
- Optimize best combination, which yields maximum sensitivity and minimum volume.

Experimental trials were conducted according to box-behnken design. Results obtained for each trial for response as sensitivity and volume are noted as shown in Table 2.

Table 2 Experimental observations for Sensitivity and volume

Trial No.	Process Parameters			Response Variables	
	Rim thickness [A] Mm	Web height [B] mm	Web thickness [C] mm	Sensitivity μstrain/N	Volume mm^3
1	7.6	19.2	3	0.038	97326.63
2	9.5	12.8	3.6	0.046	102490.29
3	11.4	12.8	3	0.054	107082.09
4	9.5	19.2	2.4	0.046	101853.01
5	9.5	12.8	2.4	0.066	101162.60
6	7.6	16	3.6	0.037	97689.15
7	7.6	16	2.4	0.052	96237.40
8	11.4	16	3.6	0.037	108270.34
9	9.5	16	3	0.044	102275.45
10	7.6	12.8	3	0.054	96511.25

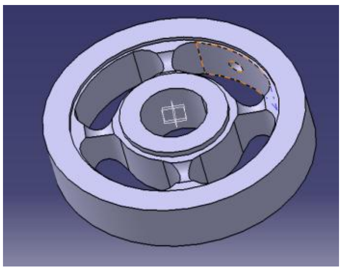
2.4. Finite Element Method

Finite element method (FEM) involves solution of engineering problems using computers. Engineering structures that have complex geometry and loads are complicated to evaluate (Kolhapure *et.al*, 2016). In FEM, a structure of this type can be easily examined. Commercial FEM programs can solve a complex engineering problem devoid of knowing governing equations or mathematics, the user is require to know the geometry of the structure and its boundary conditions. FEM software provides an entire solution including deflections, stresses, and reactions.

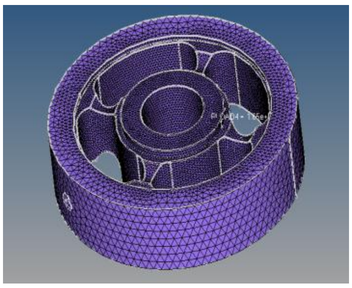
The response variables considered in this work are Sensitivity and Volume. The structural analysis of the pancake type load cell by measuring the responses for different experiments as cited in table 2 are carried out. By using CATIA software the structural model of a pancake load cell will be developed. Furthermore, the FEA performed using Hyperworks software. 3D model of load cell is imported into the HyperMesh for preprocessing. Preprocessing of the model consists of meshing, selection of material properties, creation of load collectors and apply boundary conditions on the model. Then the model is exported to RADIOSS for solving problem. Results of solution plotted in HyperView which is a well known postprocessor of HyperWorks software (Zolekar *et.al*, 2013).

To carry out analysis following assumptions was made,

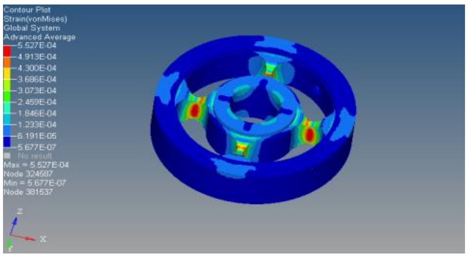
1. Bottom surface of load cell is fixed.
2. Uniformly distributed load is acting on the top surface (on the Button) of load cell.
3. At the location of strain gauge value of strain is measured.



a. 3d Model



b. Meshing Model



c. Strain

Fig.3 Steps involved in FEM process

3. Response Surface Methodology

Response surface method is used to evaluate the functions describing the relationship among some influencing factors and the process results. Box and Wilson introduced RSM in 1951 and then Montgomery and Myers [Myerse.al, 2003] developed it. The most important purpose of RSM is to use a series of designed experiments to attain an optimal response. In many cases, a second-degree polynomial model is used in RSM. This model is only an approximation, but because of its flexibility it is widely used (Almirzaloo *et.al*, 2012). This model is expressed as,

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i x_j^2 + \sum_{i=1}^{k} \beta_{ij} x_i x_j + \varepsilon_p \qquad (1)$$

Where, y is the response, β_0 , βi , βii , βij are unknown constant coefficients and xi and xj, denote the independent design variables, k is the number of the independent variables, and ε is the statistical error. The coefficients of the model equation are obtained using regression methods. The Minitab software was used to analyze the data. Each of the variables considered in three levels that are shown in Table 3.

4. Multi-Objective Optimization

The purpose of optimization is to find one or several acceptable solutions to the critical values of one or more of the objective functions. Optimization methods are important in practice, especially in engineering design, experimental test and trading decisions (Nagaile *et.al*, 2004). When a problem involves more than one objective function, finding process of the optimal response is called multi-objective optimization. Desirability function is one of the multi-objective optimization methods that is used in this study. To optimize by using desirability function, firstly the individual desirability degree for each response should be calculated. If the aim is to minimize a response, the individual desirability is calculated using Equation (2). Also, Equation (3) is used for maximizing the response.

$$d_i = \begin{cases} 0 & y_i > U_i \\ \left[\frac{(U_i - y_i)}{(U_i - T_i)}\right]^{r_i} & T_i \le y_i \le U_i \\ 1 & y_i < T_i \end{cases} \qquad (2)$$

$$d_i = \begin{cases} 0 & y_i < L_i \\ \left[\frac{(y_i - L_i)}{(T_i - L_i)}\right]^{r_i} & L_i \le y_i \le T_i \\ 1 & y_i > T_i \end{cases} \quad (3)$$

In Equations (2) and (3), *di* is the individual desirability degree, *yi* represents the predicted value, *Ti* is the target value, *Ui* denotes the maximum acceptable value, *Li* is the minimum acceptable value and *ri* represents the weight of desirability function for the *i*th response. In this research, response volume should be minimum, therefore Equation (2) is used and sensitivity should be maximum, therefore Equation (3) is used. After calculating the individual desirability degree for each function, in order to use them to combine all the answers and finding overall proper conditions, the composite desirability is obtained using Equation (4) in which *D* is the composite desirability degree, *wi* represents the importance of *i*th response and *W* is the overall weight.

$$D = (\Pi(d_i^{w_i}))^{1/w} \quad (4)$$

Since the ultimate goal of this research is to achieve the less volume and maximum sensitivity of load cell, the importance for both objective functions is considered one. Likewise the desirability function weight for each response is considered one. This is the default weight and is called linear desirability function [Camra *et.al*, 2014].

5. Results and Discussion

5.1 Effect of process parameters on Volume

By using RSM, final model for Volume according to the input parameters Rim thickness (A), Web height (B) and Web thickness (C) will be expressed as Equation (5):

$$Volume = 70235 + 2912\,A + 153.6\,B + 609.6\,C - 7.432\,A^2 - 4.057\,B^2 + 7.559\,C^2 + 0.3655\,A\times B + 2.287\,A\times C + 33.61\,B\times C \quad (5)$$

Analysis of variance (ANOVA) has been used in order to examine the effect of the parameters in the fitted regression model. The results of ANOVA for volume are presented in Table 3. The P values less than 0.05, indicates that the desired parameters are effective [Patel *et.al*, 2013]. It was observed that the terms linear, square and interaction are effective in the regression model.

Table 3 ANOVA for Response Surface Model of Volume

Source	Degree of Freedom	Seq. Sum of Square	Adj. Sum of Square	Adj. Mean Square
Regression	9	161658714	161658714	17962079
Linear	3	161642810	392220	130740
A	1	158234589	355843	355843
B	1	460764	1549	1549
C	1	2947456	1555	1555
Square	3	8751	3555	1185
A*A	1	48	921	921
B*B	1	8598	2209	2209
C*C	1	105	14	14
Interaction	3	7154	7154	2385
A*B	1	313	8	8
A*C	1	177	11	11
B*C	1	6664	6664	6664
Residual Error	0	-	-	-
Total	9	161658714		

Parameters	Degree of Freedom	Adj. Sum of Square	Adj. Mean Square	F- Value	P- Value
Rim thickness [A]	2	142855611	7.1E+07	29955	0
Web height [B]	2	817112	408556	171.3	0
Web thickness [C]	2	2394637	1197318	502.1	0
Error	3	7154	2385		
Total	9	161658714			

Figure 4 shows response surface of volume according to the rim thickness (A) and web height (B). In Figure 5 response surface of volume according to the web height (B) and web thickness (C) is shown. Also Figure 6 shows the response surface of volume according to the rim thickness (A) and web thickness (C).

According to Figures 4 to 6, it is clear that with increasing rim thickness (A), web height (B) and web thickness (C) volume is increased. In the other words, by reduction of the rim thickness, web height and web thickness of the pancake type load cell, the volume of the load cell will be reduced. Also, according to the ANOVA and the fact that the P value is less than 0.05, all of the three parameters affect the volume.

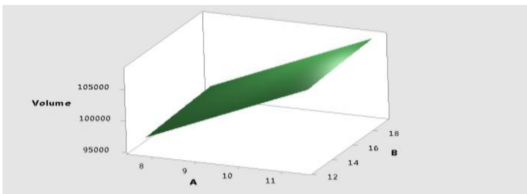


Fig.4 Response surface of volume according to rim thickness (A) and web height (B)

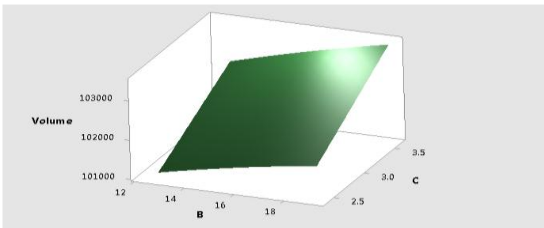


Fig.5 Response surface of volume according to web height (B) and web thickness (C)

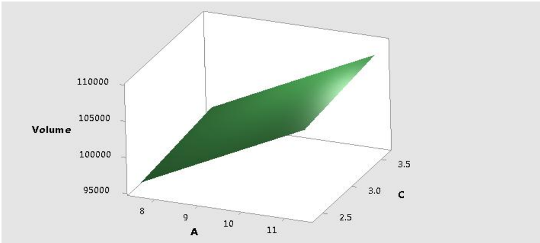


Fig.6 Response surface of volume according to rim thickness (A) and web thickness (C)

5.2 Effect of process parameters on Sensitivity

By using RSM, final model for Volume according to the input parameters Rim thickness (A), Web height (B) and Web thickness (C) will be expressed as Equation (6):

$$\text{Sensitivity} = 267.1 + 3.421\,A - 15.31\,B - 52.50\,C - 0.1731\,A^2 + 0.2808\,B^2 + 3.819\,C^2 + 0.04112\,A\times B - 0.2193\,A\times C + 1.172\,B\times C \quad (6)$$

The results of ANOVA for sensitivity are tabulated in Table 4. It was observed that the terms linear, square and interaction are effective in the regression model.

Table 4 ANOVA for Response Surface Model of Sensitivity

Source	Degree of Freedom	Seq. SS	Adj. SS	Adj. MS
Regression	9	0.000774	0.000774	0.000086
Linear	3	0.000756	0.000022	0.000007
A	1	0.000004	0	0
B	1	0.000305	0.000015	0.000015
C	1	0.000448	0.000012	0.000012
Square	3	0.000009	0.000013	0.000004
A*A	1	48	921	921
B*B	1	8598	2209	2209
C*C	1	105	14	14
Interaction	3	7154	7154	2385
A*B	1	313	8	8
A*C	1	177	11	11
B*C	1	6664	6664	6664
Residual Error	0	-	-	-
Total	9	161658714		

Parameters	Degree of Freedom	Adj. Sum of Square	Adj. Mean Square	F- Value	P- Value
Rim thickness [A]	2	0.11	0.055	0.02	0.982
Web height [B]	2	410.163	205.082	67.12	0.003
Web thickness [C]	2	342.033	171.017	55.97	0.004
Error	3	9.167	3.056		
Total	9	774.4			

Figure 7 shows response surface of sensitivity according to the rim thickness (A) and web height (B). In Figure 8 response surface of sensitivity according to the web height (B) and web thickness (C) is shown. Also Figure 9 shows the response surface of sensitivity according to the rim thickness (A) and web thickness (C).

According to Figures 7 to 9, it is clear that with increasing rim thickness (A), web height (B) and web thickness (C) sensitivity of pancake type load cell is increased.

Also it can be seen that the effect of rim thickness on the sensitivity is not notable. This matter can be seen from ANOVA table of thinning ratio. Because the P value for rim thickness is greater than 0.05.

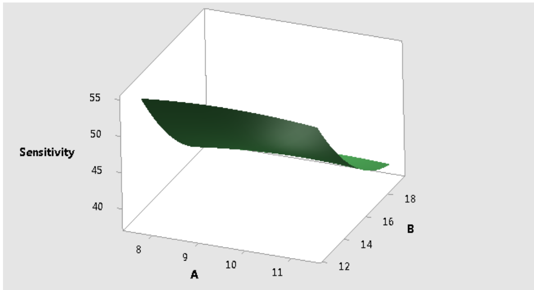


Fig.7 Response surface of sensitivity according to rim thickness (A) and web height (B)

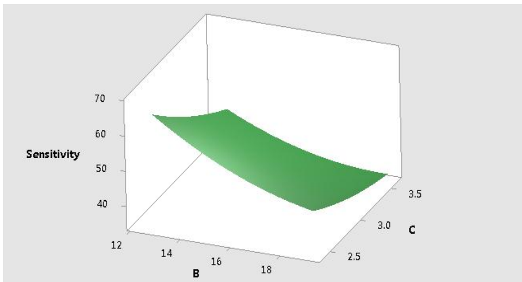


Fig.8 Response surface of sensitivity according web height (B) and web thickness (C)

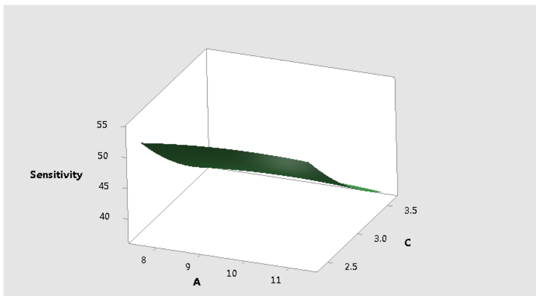


Fig.9 Response surface of sensitivity according to rim thickness (A) and web thickness (C)

5.3 Optimization Process

In order to use the desirability function, an area should be specified to obtain optimum point. The volume should be minimum and sensitivity should be maximum. For this issue, first the target and the upper bound should be determined (Alimirzaloo, 2016). For the response volume, the target value is selected 96237. This value is considered from run number 7 of Table 2 in which the lowest volume for pancake type load cell is obtained. Also the upper bound is selected 108270 which is considered from run number 8 of table 2.For the response sensitivity the target value selected is 0.66 which is maximum selected from run number 5 of table 2. The optimization results using the mentioned information are shown in Figure 10. According to this figure, the composite desirability of the obtained point is 0.9863. Because this amount is higher than 0.9, it can be selected as the accepted optimal point. Table 5 shows the optimal point values.

In order to evaluate the optimal point, the FE results of this point were compared with the results of the normal simulation. The results show the improvement of the sensitivity of pancake type load cell with optimal point values by 43% in optimized model compared to the original model. Also there is reduction in volume by 7% in optimized model compared to original model as shown in table 6.

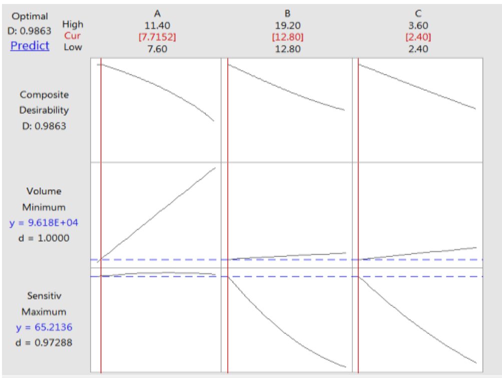


Fig.10 Optimization curves using desirability function

Table 5 Optimal point values using desirability function

Parameter	values
Rim thickness [A]	7.71
Web height [B]	12.80
Web thickness [C	2.40

Table 6 Experimental Validations of Developed Models with Optimal Parameter Settings

Responses	Original load cell	Optimized load cell	
		Predicted (RSM)	Experimental (FEM)
Sensitivity (µ strain/N)	0.037	0.0652	0.0652
Volume (mm^3)	102275.55	96175.3	95880.36

Conclusions

The Present study focused on Multi response optimization of Volume and Sensitivity of load cell. Response Surface Methodology of experimental results of Volume and Sensitivity can covert multiple performance characteristics with desirability function.

A Few conclusions are drawn based on experimental study are as follows;

1] The experimental results shows that, minimum volume and maximum sensitivity is achieved by optimal combination, Rim thickness of 7.7152mm, Web height of 12.80mm and Web thickness of 2.40mm in manufacturing of load cell and this is achieved by using RSM method.

2] From ANOVA results, it reveals that the Rim thickness of load cell is the most significant parameter for minimizing volume and Web height for maximizing sensitivity.

Acknowledgement

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