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NUMERICAL TEST OF LOWER ARM VEHICLE USING FINITE ELEMENT ANALYSIS AND STATISTICAL METHOD

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ABSTRACT

The aim of this study to investigate the influencing factors of the lower suspension arm by integrating finite element technique with response surface methodology (RSM). Response surface methodology has been widely used to predict stress von Mises on lower arm systems models. Aluminum alloys (AA7075-T6) are selected as a suspension arm materials. The structural model of the suspension arm was developed utilizing the Solid works. The finite element model and analysis were performed utilizing the finite element analysis code. The finite element model is correlated with design of experiments (DOE) modal test. Influences of the various factors namely; mesh size, load are investigated using RSM. A mathematical prediction model has been developed based on the most influencing factors and the validation simulation analysis proved its adequacy. The results show that there is no abnormality in the methodology adopted (R^2 =0.8406). Ratio greater than 4 is desirable; Model's ratio of 8.183 indicates an adequate signal. The Model F-value of 5.65 implies the model is significant. RSM was used to design the experiments and analyzed the results obtained. RSM aimed towards prediction stress on lower arm through the various factors of the suspension arm geometrical construction.

Keywords: Numerical test, RSM, FEA, Suspension arm

التحليل العددي لمركبة ذراع التعليق السفلي بأستخدام طريقة العناصر المحددة وطريقة أحصائية

نصير حامد فرهود

الخلاصة

تهدف هذه الدراسة إلى معرفة العوامل المؤثرة في ذراع التعليق السفلي بدمج تقنية العناصر المحدودة مع منهجية سطح الاستجابة (RSM). تم استخدام منهجية سطح الاستجابة على نطاق واسع للتنبؤ بالإجهاد فون ميزس في نماذج أنظمة الذراع السفلى. يتم اختيار سبائك الألومنيوم (AA7075-T6) كمواد ذراع تعليق. تم تطوير النموذج الهيكلي لذراع التعليق باستخدام الأعمال الصلبة. تم إجراء تحليل ونموذج العنصر المحدود باستخدام كود تحليل العناصر المحدودة. يرتبط نموذج العناصر المحدودة بتصميم التجارب النموذجية (DOE). تأثيرات العوامل المختلفة وهي؛ حجم الشبكة، يتم فحص الحمل باستخدام تقنية RSM. تم تطوير نموذج التنبؤ الرياضي بناءً على العوامل الأكثر تأثيرًا وأثبت تحليل محاكاة التحقق كفاءته. أظهرت النتائج عدم وجود شذوذ في المنهجية المتبعة ($R^2 = 0.8406$). النسبة الأكبر من 4 مرغوبة؛ تشير نسبة الطراز 8.183 إلى أن الأشارة مناسبة. في حين تشير قيمة النموذج F البالغة 5.65 إلى أن النموذج مهم. تم استخدام RSM لتصميم التجارب وتحليل النتائج التي تم الحصول عليها. تهدف RSM إلى التنبؤ بالإجهاد على الذراع السفلي من خلال العوامل المختلفة للتركيب الهندسي لذراع التعليق.

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INTRODUCTION

The use of statistical design of experiment (DOE) techniques combined with finite element analysis (FEA) provides the engineering community with valuable tools for forecasting the behavior of a system or process. With the use of orthogonal polynomial expansion techniques, experimental results can be effectively transformed into mathematical equations based on the strength of the various factors and associated interactions. Conle and Mousseau (1991) used the vehicle simulation and finite element result to generate the fatigue life contours for the chassis component using automotive proving ground load history result combine with the computational techniques. They concluded that the combination of the dynamics modeling, finite element analysis is the practical techniques for the fatigue design of the automotive component. Kim et al. (2002) was studied a method for simulating vehicles dynamic loads, but they add durability. Nadot and Denier (2004) have been studied fatigue phenomena for nodular cast iron automotive suspension arms. The authors found that the major parameter influencing fatigue failure of casting components was casting defects. Rahman et al. (2007) were used finite element analysis to predict the fatigue life and discussed identify the critical locations of two- stroke free piston linear engine component using variable amplitude loading. The linear static finite element analysis was performed using MSC NASTRAN. Finally author showing the contour plots of the fatigue life histogram and damage histogram at the most critical location. The DOE and FEA combination allows the engineer to study a range of boundary conditions for numerous design factors and to analyze the impact and associated response for each factor and interaction within the system Nye L. W. (1996). Hu et al. (1999) investigated optimal design based on the DOE analysis was the one that used the original finger length, the vertical slot, the chamfer pad, the 28mm thickness of disc, and the 10mm thickness of friction material. Central composite design (CCD) is one of the most important experimental designs used for optimizing parameters; CCD is far more efficient than running 3K factorial design with quantitative factors Montgomery (2005). RSM is an important methodology used in developing new processes, optimizing their performance, and improving the design and/or formulation of new products. It is often an important concurrent engineering tool in which product design, process development, quality, manufacturing engineering, and operations personnel often work together in a team environment to apply RSM. It is a dynamic and foremost important tool of design of experiment (DOE), where in the relationship between responses of a process with its input decision variables is mapped to achieve the objective of maximization or minimization of the response properties Myers et al. (2002). In this paper, the RSM has been applied to develop a mathematical model to predict the stress for lower arm vehicle by integrating the FE analyses with structured DOE. Finite element techniques have been used as a tool to model the mechanical properties of the suspension arm. Three-dimensional linear tetrahedron solid elements (TET10) used for the initial analysis based on the loading conditions and it was subsequently validated using finite element analysis. The accuracy of the model has been tested using the analysis of variance (ANOVA) with the aid of a statistical design of experiment software called Design-Expert version 6.0. Knowledge of tool life will help the process planner or operator in selecting the optimum parameters to minimize the stress.

RESPONSE SURFACE METHODOLOGY

RSM is a collection of mathematical and statistical techniques that are useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response Montgomery (2001). RSM also quantifies relationships among one or more measured responses and the vital input factors (Design-Expert Software V.8.0).

Test for significance of the regression model

This test is performed as an ANOVA procedure by calculating the F-ratio, which is the ratio between the regression mean square and the mean square error. The F-ratio, also called the variance ratio, is the ratio of variance due to the effect of a factor (in this case the model) and variance due to the error term. This ratio is used to measure the significance of the model under investigation with respect to the variance of all the terms included in the error term at the desired significance level, a significant model is desired.

Test for significance on individual model coefficients

This test forms the basis for model optimization by adding or deleting coefficients through backward elimination, forward addition or stepwise elimination/addition/exchange. It involves the determination of the P-value or probability value, usually relating the risk of falsely rejecting a given hypothesis. For example, a “Prob. > F” value on an F-test tells the proportion of time you would expect to get the stated F-value if no factor effects are significant. The “Prob. > F” value determined can be compared with the desired probability. In general, the lowest order polynomial would be chosen to adequately describe the system.

Test for lack-of-fit

As replicate measurements are available, a test indicating the significance of the replicate error in comparison to the model dependent error can be performed. This test splits the residual or error sum of squares into two portions, one which is due to pure error which is based on the replicate measurements and the other due to lack-of-fit based on the model performance. The test statistic for lack-of-fit is the ratio between the lack-of-fit mean square and the pure error mean square. As previously, this F-test statistic can be used to determine as to whether the lack-of-fit error is significant or otherwise at the desired significance level. Insignificant lack-of-fit is desired as significant lack-of-fit indicates that there might be contributions in the regressor–response relationship that are not accounted for by the model. The checks performed here include determining the various coefficients of determination R^2 coefficients which ranged between 0 and 1. In addition to the above, the adequacy of the model is also investigated by the examination of residuals Montgomery (1997). The residuals, which are the difference between the respective, observe responses and the predicted responses are examined using the normal probability plots of the residuals and the plots of the residuals.

MECHANICAL PROPERTIES

Material model and material properties play an important role in the result of FE method. The material properties are one of the major inputs, which is definition of how the material behaves under the cyclic loading conditions. The materials parameters required depend on the analysis methodology being used. The mechanical properties of 7075-T6 aluminum alloy are shown in Table (1). AA7075-T6 has been chosen the for lower suspension arm because of his advantage like excellent joining characteristics, good workability, high resistance to corrosion and lightweight.

FINITE ELEMENT MODELING AND ANALYSIS

The suspension arm was modeled using, MSC Nastran, Finite element analysis software. The premise was to model a lower arm structure and verify that the two techniques, theoretical and computer provided the same answer. Stress analyses considering the ultimate load condition, Seo et al. (2007) applied to the parts during the driving was performed. Table (2) shows the five ultimate load conditions of the lower arm. The Pothole brake limit load is the condition applied to the lower arm in the case of simultaneous falling into a pit and braking; the oblique kerb limit load is the condition in the case of traversing the inclined curve road; the Pothole corner limit load is the condition in the case of driving the corner of a pit; the lateral kerb strike limit load is the condition in the case of turning along a side curve; the ultimate vertical limit load is the maximum vertical load condition applied to the lower arm. A simple three-dimensional model of suspension arm was developed using SolidWorks software as shown in Figure (1). The three-dimensional FE model, loading and constraints of suspension arm is shown in Figure (2). The boundary conditions as shown in Figure (2) and the mechanical properties of the material for the lower arm were input into MSC. Patran and 10 node tetrahedral element (TET10) was used for the solid mesh.

METHODOLOGY

Human made products or processes can be treated like a system, if it produces a set of responses for a given set of inputs. Suspension system can also be treated like a system as shown in Figure (3). Some systems like suspension system produce unwanted outputs namely squeal for a set of inputs parameters. The present study was aimed at establishing the input-output relationships for prediction load and property (mesh size) of lower suspension arm. Suspension system has numerous variables, In order to arrive at the most influential variables and its effects a phase strategies were proposed. CCD based Response surface methodology (RSM) was deployed to develop a linear model for prediction of Lower arm.

NUMERICAL RESULTS AND ANALYSIS USING CCD

This section discusses about the two phases of experiments, its results, developed mathematical models of the system and its adequacy. In light of the screening experiments, a decision was taken to study the effects of the top four factors, namely; Mesh size, Load X, Y, Z. The variables and their levels are listed in Table (3). Different terms used in the Table (4) are as follows. The term ‘DF’ means degrees of freedom. The DF refers to the number of terms that will contribute to the error prediction. The term ‘Seq. SS’ represents the sum of squares for each term, which measures the variability in the data contributed by the term. The Model F-value of 5.65 implies the model is significant. There is only a 0.10% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant based on central composite design technique. In this case C, B^2, C^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. Moreover, the design showed insignificant lack of fit (F-value = 0.34), which is desirable, related to the pure error and this means there is a 9.292 % chance that lake of fit could have occurred due to noise. The response equation for von Mises in coded form is given below with equation (1).

$$
\begin{aligned}
vonMises &= 317.12-17.56*A-8.17*B+150.39*C+21.28*D+21.63*A*B \\
&+37.88*A*C-53.00*A*D+12.25*B*C-35.78*B*D-52.88*C*D \qquad (1) \\
&-134.25*A^2+251.25*B^2+309.25*C^2-101.75*D^2
\end{aligned}
$$

where, the amount of von Mises in term a function of mesh size (A), load x (B), load y (C), and load z (D). The coefficient with one factor represents the effect of the particular factor, while the coefficient with two factors or more represents the interaction between these factors. The positive sign in front of the terms indicates synergistic effect, while negative sign indicates antagonistic effect. The graphical representations of the model (equation 1) facilitate an examination of the effects of the experimental factors on the response. 3D response surface is a representation of the fitted response function, and they were obtained using the Design-Expert software. The effects of mesh size and load z dose interaction on Mises are presented in Figure (4) by 3D and 2D plots. It can be observed that the maximum von Mises of 300 MPa and the minimum von Mises of 200 MPa occurred at 5 -6 of reaction mesh size and -66.7 N -845.9 N of load z, respectively. The effect of load x and load y dose interaction on von Mises are presented in Figure (5) by 3D and 2D plots. It can be observed that the maximum von Mises of 780 MPa and the minimum von Mises of 500 MPa occur at 1945.75 N, -9579.70 N of reaction load x and -4801.20 N, -12218.30 N of load y, respectively.

The following observations can be made from the surface plots: Figure (6) shows the normal probability plot of residuals. It shows that there is no abnormality in the methodology adopted (R^2 =0.8406). The R^2 analysis is tabulated in Table 5. The "Pred R-Squared" of 0.5120 is in reasonable agreement with the "Adj R-Squared" of 0.6919. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable; Model’s ratio of 8.183 indicates an adequate signal. In fact, when the value of correlation coefficient R is close to 1, it means the response correlation (linear correlation between variables) FEA result and predicted values are better. The statistical analysis shows that, the developed linear model based on central composite design is statistically adequate and can be used to navigate the design space.

Figure (7) is the predicted versus actual plot shows how the model predicts over the range of data. Plot should exhibit random scatter about 45-degree line and the clusters indicate problems of over or under predicting. The best fit line plot (Figure (7)) of the 30 points (Table 6) was found to be close to the ideal Y = X line; predicted responses show good agreement with actual results; The scatter shows the bowling scores can be predicted very precisely. Table (6) lists the comparison between predicted versus actual simulation and gives the factor settings, predicted responses, measured von Mises and percentage deviation for each run, a total number of thirty trials were conducted and a set of data was collected as per the structure of CCD of experiments. Figure (8) shows the percentage deviation plot, actual results varied between -16.5 % and 22.4 % from predicted responses. This indicates that designed model space can be navigated for prediction.

CONCLUSIONS

Statistical techniques together with good engineering knowledge and common sense will usually lead to sound conclusions. Linear model for the lower arm based on Central composite design of experiments was successfully developed, statistically adequate and can be used to navigate the design space. To validate the model, randomly generated twenty one test cases were examined. Continued research in this direction can bring about more comprehensive and appropriate guide lines for designers. The combined approach of modeling lower arm using CEA and DOE is found to be statistically adequate through verification trials.

Table (1): Mechanical properties of aluminum alloy 7075-T6

Material	**Young’s Modulus (GPa)**	**Poisson’s ratio**	**Tensile strength (MPa)**	**Yield strength (MPa)**
Aluminum alloy AA7075-T6	72	0.33	570	490

Table (2): Load conditions of lower arm

Case	**Conditions**		**Load (N)**	
		X	**Y**	**Z**
1	Pothole brake limit load	−5688.2	−4801.2	−60.4
2	Oblique kerb limit load	9579.7	2382.1	238.3
3	Pothole corner limit load	−1107.0	1108.3	197.6
4	Lateral kerb strike limit load	−549.7	12218.3	845.9
5	Ultimate vertical limit load	−573.7	−3408.9	-66.7

Table (3): Coded levels of variable and actual values for CCD

Factor			Level	
Coded	**Uncoded**	**Units**	**Low**	**High**
A	Mesh size	-	5	7
B	Load X	N	-5688.2	9579.7
C	Load Y	N	-4801.2	12218.3
D	Load Z	N	-66.7	845.9

Table (4): Analysis of variance by ANOVA for response surface model

Source	**DF**	**Sum of Square (Seq. SS)**	***F* value**	***Prob>F***
Model	14	1487000	5.65	0.0010 significant
A- Mesh size	1	5547.56	0.3	0.5949
B-Load x	1	1200.50	0.064	0.8039
C-Load y	1	407100	21.66	0.0003
D-Load z	1	8149.39	0.43	0.5202
AB	1	7482.25	0.4	0.5375
AC	1	22952.25	1.22	0.2865
AD	1	44944.00	2.39	0.1428
BC	1	2401.00	0.13	0.7257
BD	1	20592.25	1.1	0.3118
CD	1	44732.25	2.38	0.1437
A^2	1	46693.07	2.48	0.1358
B^2	1	163600	8.7	0.0099
C^2	1	247800	13.19	0.0025
D^2	1	26821.53	1.43	0.2508
Residual Error	15	281900		
Lack-of-Fit	10	114800	0.34	0.09292 not significant
Pure Error	5	167100		

* $P < 0.05$ indicate the term is significant

Table (5): R^2 analysis

Std. Dev.	137.09
Mean	511.83
C.V. %	26.78
PRESS	863300
R-Squared	0.8406
Adj R-Squared	0.6919
Pred R-Squared	0.5120
Adeq Precision	8.183

Table (6): Comparison between predicted versus actual simulation

Run No.	**A: Mesh size**	**B: Load X**	**C: Load Y**	**D: Load Z**	**Actual FEA**	**Predicted DOE**	**Residual**	**% Deviation**
1	6.00	9579.70	3708.55	389.60	410.00	425.70	-15.70	-3.65
2	6.00	1945.75	3708.55	-66.70	295.00	277.58	-82.58	5.9
3	7.00	-5688.2	-4801.2	-66.70	410.00	413.36	-3.36	-0.82
4	6.00	1945.75	-4801.2	389.60	501.00	451.75	49.25	9.83
5	7.00	-5688.2	12218.3	845.90	672.00	731.97	-59.97	-8.9
6	6.00	1945.75	3708.55	389.60	910.00	835.36	74.64	8.2
7	6.00	1945.75	12218.3	389.60	848.00	768.64	79.36	9.35
8	5.00	1945.75	3708.55	389.60	905.00	958.53	-53.53	-0.59
9	5.00	-5688.2	-4801.2	-66.70	790.00	751.75	38.25	4.84
10	6.00	1945.75	3708.55	845.90	422.00	491.64	-69.64	-16.5
11	6.00	1945.75	3708.55	389.60	531.00	595.92	-64.92	-12.22
12	5.00	9579.70	12218.3	845.90	467.00	422.31	44.69	9.56
13	7.00	9579.70	12218.3	-66.70	807.00	846.53	-39.53	-4.89
14	6.00	1945.75	3708.55	389.60	726.00	737.92	-11.92	-1.64
15	5.00	9579.70	12218.3	-66.70	807.00	739.70	67.30	8.3
16	7.00	-5688.2	-4801.2	845.90	743.00	717.58	25.42	3.42
17	5.00	-5688.2	12218.3	845.90	199.00	200.43	-1.43	-0.71
18	7.00	9579.70	-4801.2	-66.70	189.00	165.32	23.68	12.52
19	6.00	-5688.2	3708.55	389.60	743.00	576.54	166.46	22.4
20	7.00	-5688.2	12218.3	-66.70	416.00	460.21	-144.21	-10.62
21	7.00	1945.75	3708.55	389.60	580.00	475.99	104.01	17.93
22	5.00	-5688.2	12218.3	-66.70	695.00	776.77	-81.77	-11.76
23	7.00	9579.70	12218.3	845.90	206.00	194.10	11.90	5.77
24	5.00	-5688.2	-4801.2	845.90	247.00	236.65	10.35	4.1
25	6.00	1945.75	3708.55	389.60	188.00	207.12	-129.12	-10.17
26	6.00	1945.75	3708.55	389.60	542.00	517.12	224.88	4.59
27	5.00	9579.70	-4801.2	-66.70	542.00	517.12	224.88	4.59
28	6.00	1945.75	3708.55	389.60	188.00	217.12	-129.12	-15.48
29	5.00	9579.70	-4801.2	845.90	188.00	217.12	-129.12	-15.48
30	7.00	9579.70	-4801.2	845.90	188.00	217.12	-129.12	-15.48

% Deviation = [(actual value – predicted value)/actual value] × 100

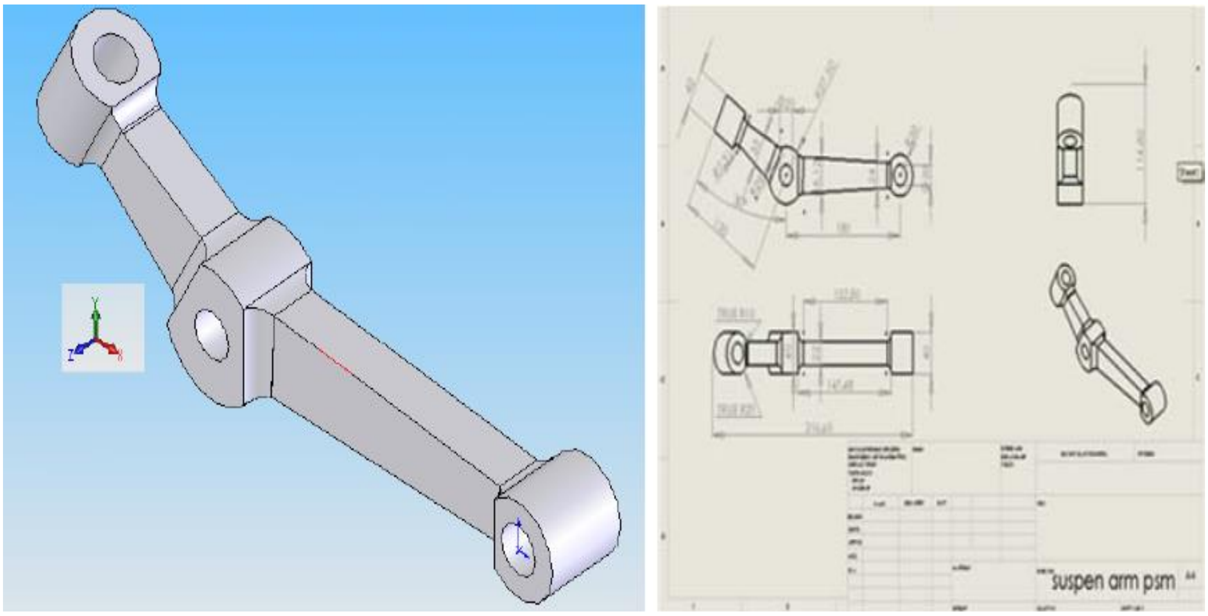


Fig. (1): Structural model and overall dimension of suspension arm

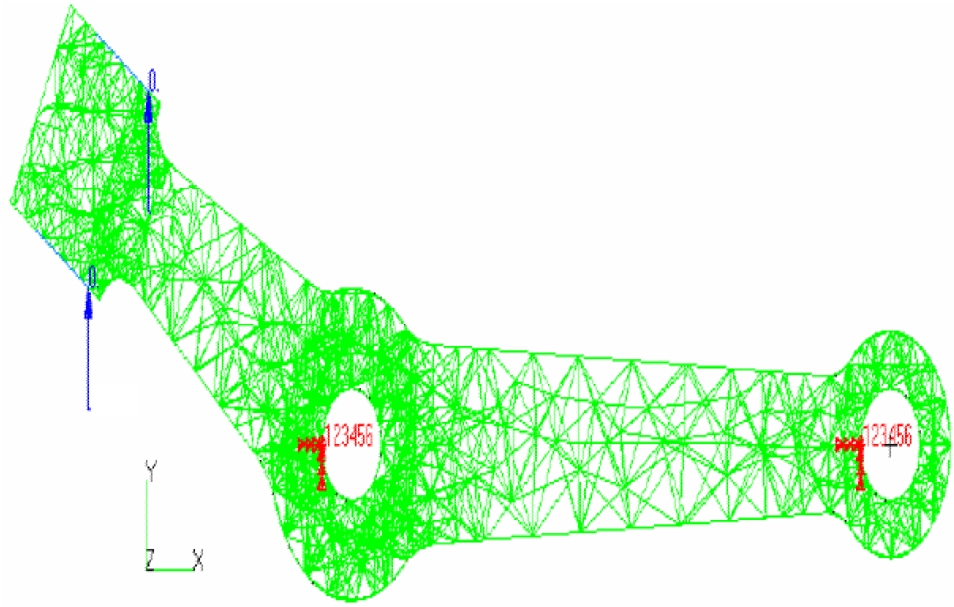


Fig. (2): Boundary conditions of lower arm

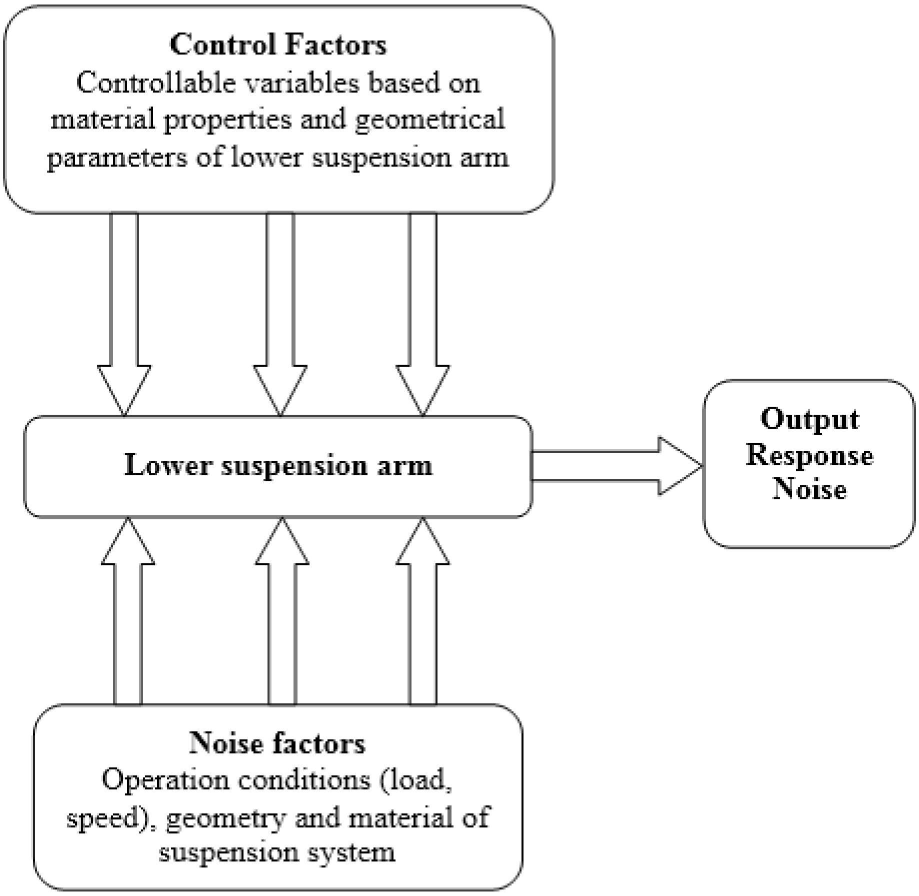
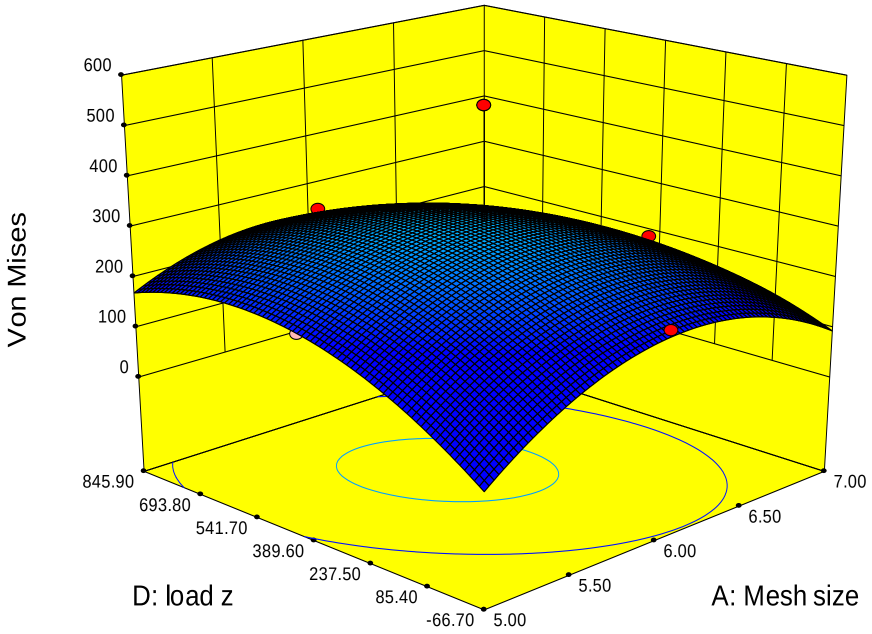
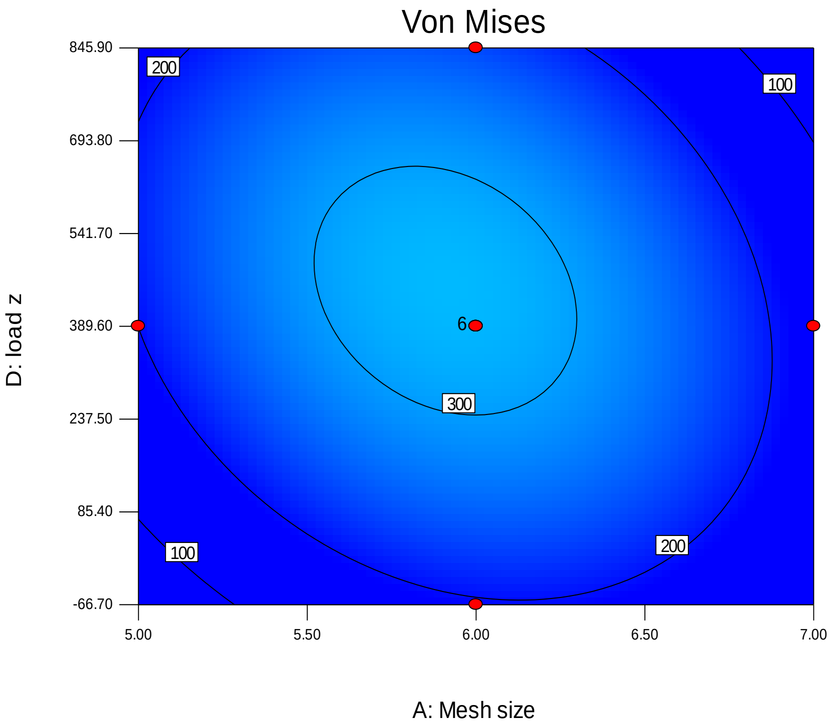


Fig. (3): Suspension system

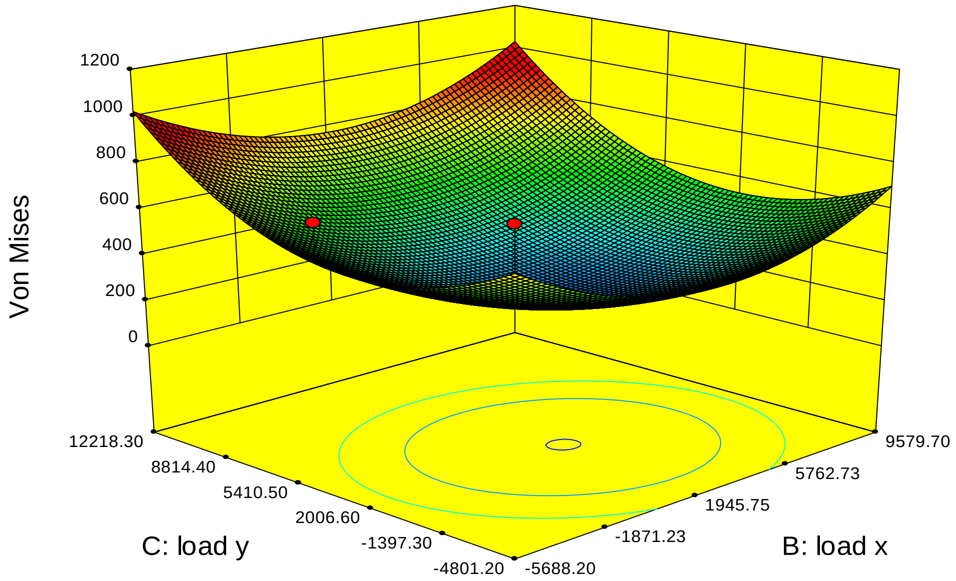


(a) 3 Dimension

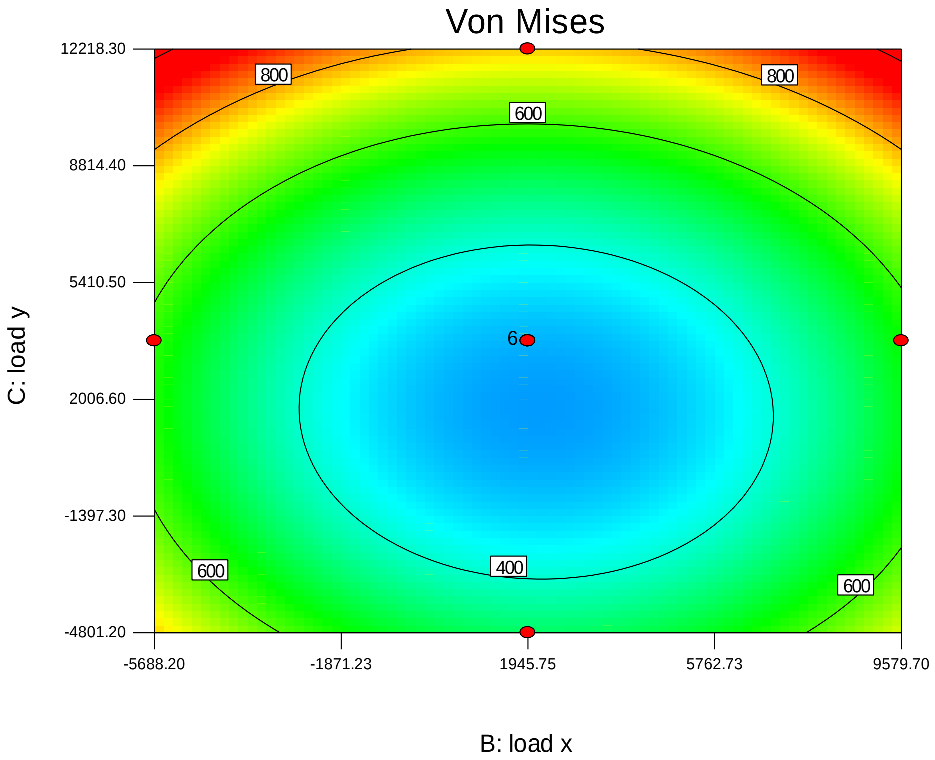


(b) 2 Dimension

Fig. (4): The interaction between mesh size and reaction load z on von Mises



(a) 3 Dimension



(b) 2 Dimension

Fig. (5): The interaction between load x and reaction load y on von Mises

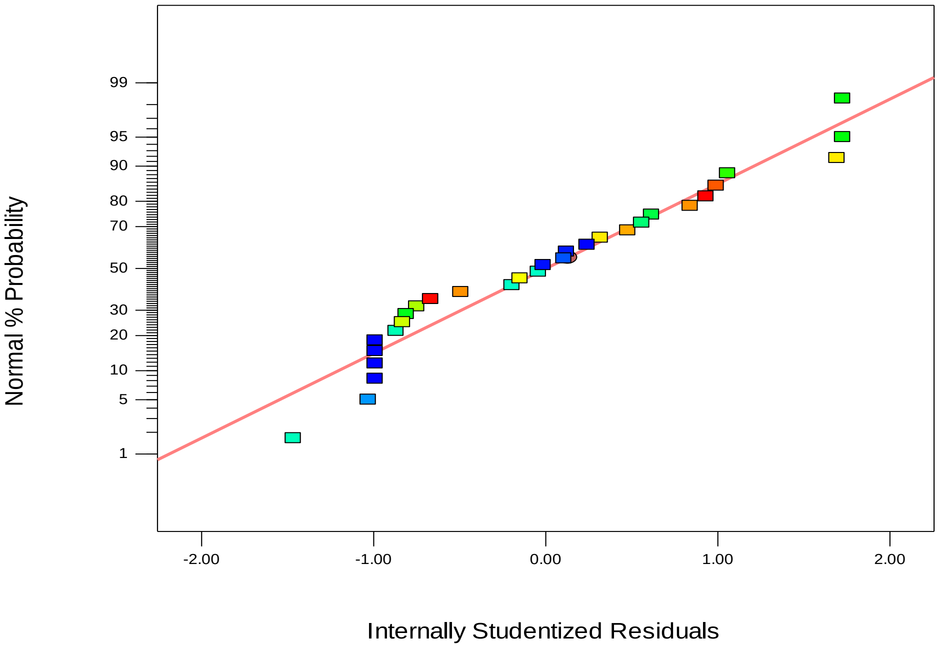


Fig. (6): Normal probability plot for residuals

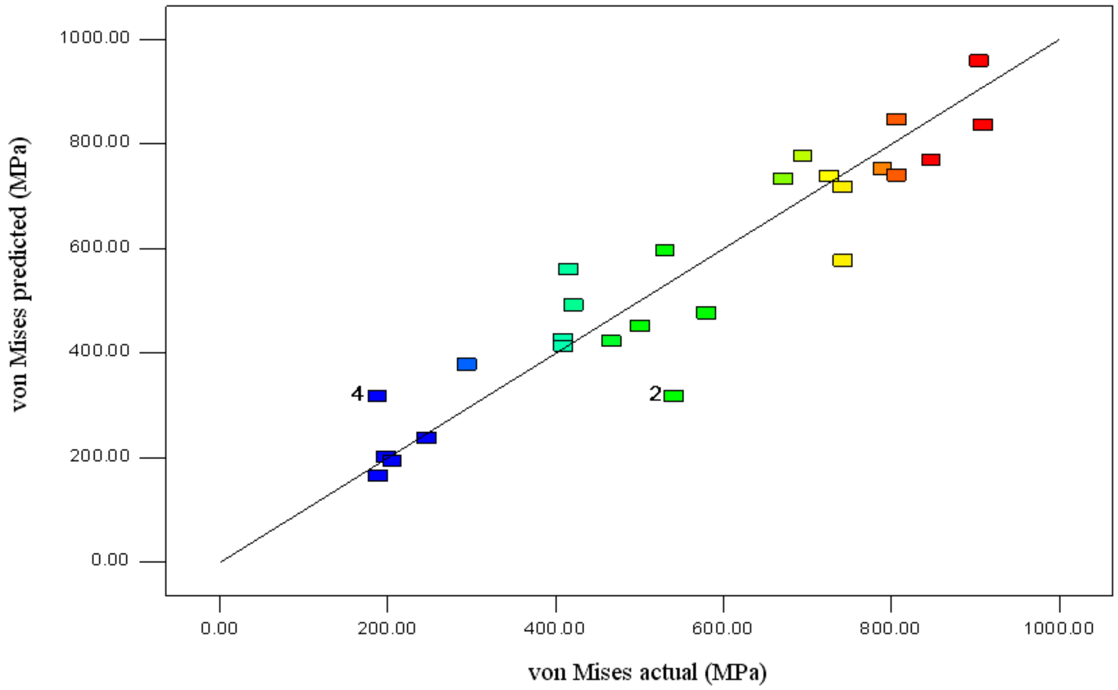


Fig. (7): The best fit line plot

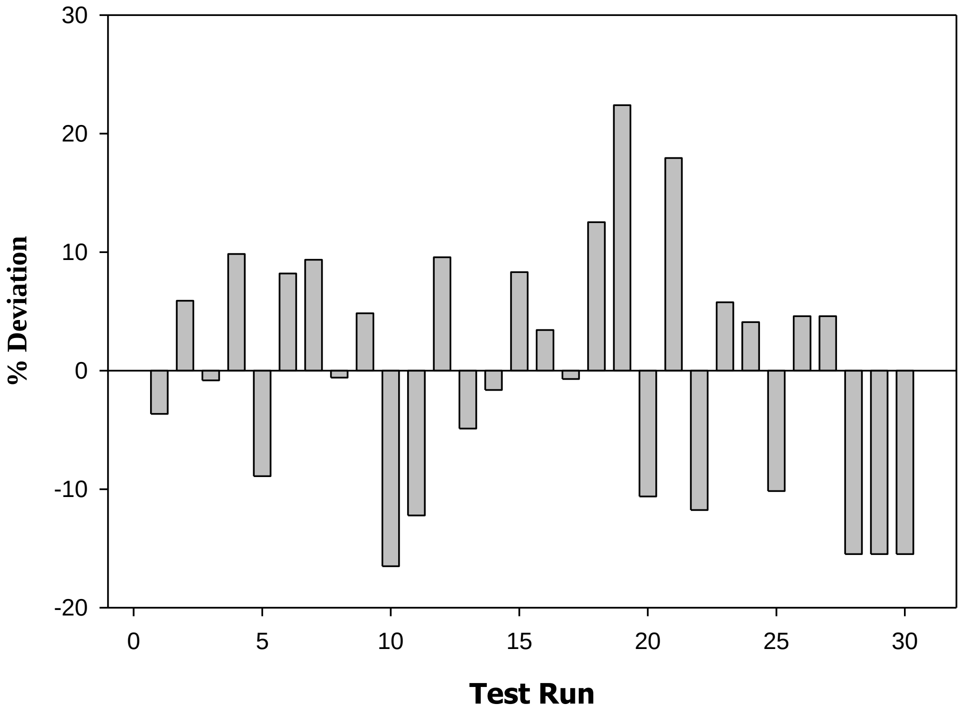


Fig. (8): Percentage deviation of FEA with DOE results

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